APPLYING MATHCAD TO THE HIGHWAY CAPACITY MANUAL

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Presented to
The Academic Faculty

By

José Alfredo Fernández León

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APPLYING MATHCAD TO THE HIGHWAY CAPACITY MANUAL

Approved by:

Dr. Glenn J. Rix, Advisor

Dr. Michael Hunter

Dr. John Leonard

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SUMMARY

The objective of this study was to develop a tool for engineers and researchers to understand the underlying logic of the Highway Capacity Manual (HCM) procedures. The HCM offers a collection of methodologies and techniques for estimating the capacity and evaluation of the level of service for highway, street and transit facilities (HCM 2000). Mathcad worksheets were developed to replicate the computational procedures of five chapters of the HCM. The principal topics addressed are advantages of the Mathcad worksheets over existing implementations of the HCM, challenges associated with the implementation, and changes and additions made to the format of the HCM worksheets reflecting capabilities and limitations of Mathcad. These dynamic documents allow the user to easily explore the sensitivity of the procedures to varying equations, relationships and input parameters. Because the Mathcad worksheets display information in a manner similar to the HCM, most users will find the worksheets straightforward to use and interpret. As such the Mathcad worksheets offer better transparency than other implementations of the HCM procedures.

CHAPTER 1

INTRODUCTION

The Highway Capacity Manual (HCM) offers a collection of methodologies and techniques for estimating the capacity and evaluation of the level of service for highway (including freeways and intersections) and street facilities (including transit, bicycles and pedestrians) (HCM 2000). Existing implementations of HCM have some drawbacks associated with them. They are either coded in a low-level programming language such as C or in non-intuitive spreadsheets that have complicated macros and hidden cells and equations. These limitations have caused two significant problems. First, the domain knowledge and the inner workings of the procedures are known only to the few active members of each subcommittee that maintains the procedures including the Signalized and Unsignalized Intersections subcommittees among others. Second, as the procedures have gotten more complicated, the tasks of verification and validation of the procedures themselves have become a significant burden on the committees.

The purpose of this study was to develop a tool for engineers and researchers to understand and manipulate the underlying logic of the HCM procedures. Dynamic Mathcad documents offer several benefits over the traditional static documents. These documents allow: 1) direct implementation of the complex procedures of the HCM in their native form, 2) exploration of the sensitivity of the procedures to varying equations, relationships and input parameters, 3) evaluation of impact of changes derived from other research on HCM procedures and 4) better transparency and thus better understanding the HCM procedures.

Mathcad Overview

Mathcad[1] provides an "integrated environment for performing, communicating and publishing math-related work." It includes a large number of operators and built-in functions to solve mathematical problems. Mathcad can be used for numerical calculations or to determine symbolic solutions. Its computational capabilities range from simple addition, subtraction, multiplication, and division to evaluating derivatives and integrals, solving systems of equations, and many other advanced functions. Mathcad can perform operations involving scalars, vectors, and matrices and automatically tracks and converts units. Programming constructs such as loops and conditional statements can also be used in MathCad to perform more complex computations.

Mathcad worksheets combine the interface of a spreadsheet with the interface of a word processor. Equations written in the Mathcad interface appear as they do in print and are "live"; as soon as a change is made to an equation or input parameters, Mathcad automatically updates the results. The user interface also allows making annotations for each step of the calculation process with text and graphics, facilitating review and publication of the worksheet. A MathCad worksheet containing brief examples of many of these features is shown in Figure 1.

Text, equations and graphics can be placed anywhere in the worksheet, but must take into account that computations flow from left to right and from top to bottom in the worksheet. This means that the input parameters for an equation or function must be defined to the left or above the equation or function. To fulfill this requirement, it was not always possible to maintain the same visual appearance of the HCM worksheets when they were implemented in Mathcad.

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[1] Mathcad is a registered trademark of Mathsoft Engineering & Education, Inc., Cambridge, MA

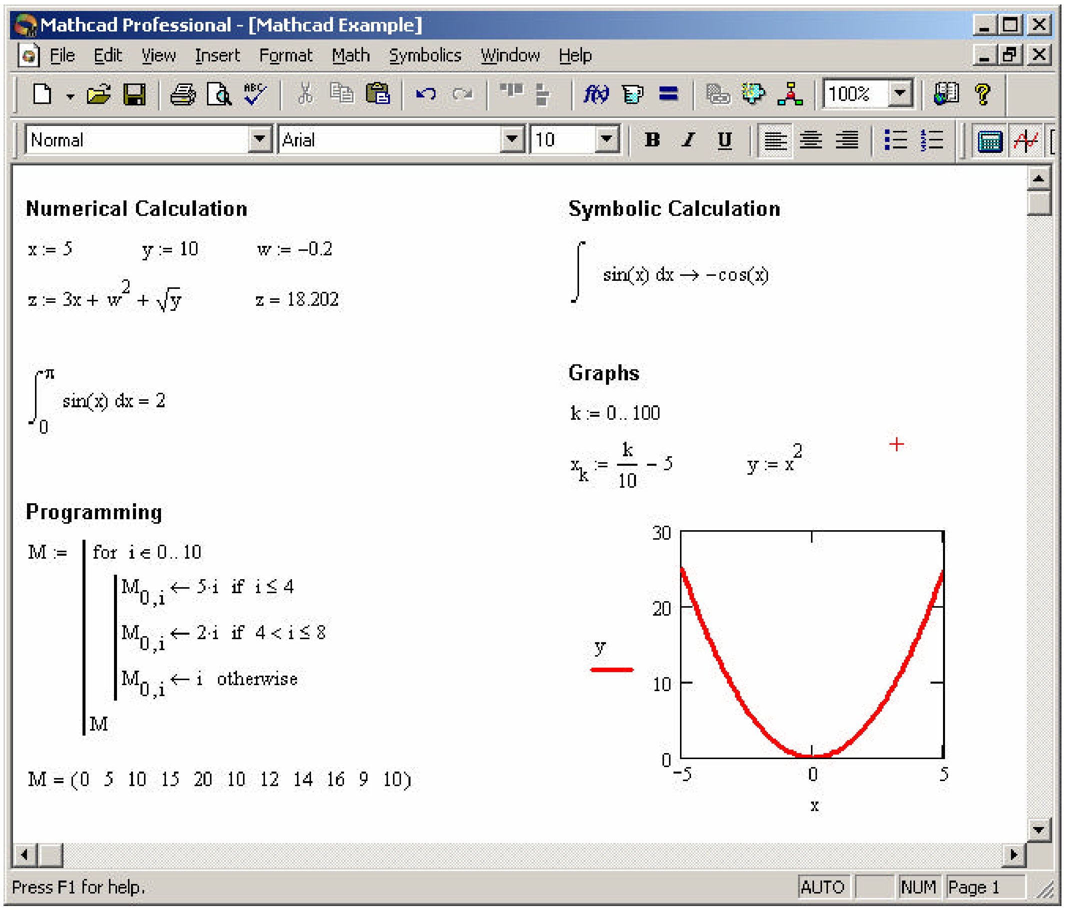


Figure 1. Example of a Mathcad worksheet

To simplify the user interface and conserve space on the worksheets, Mathcad allows hiding specific areas, which can subsequently be expanded or collapsed by the user. This feature was widely used on this project to simplify the visual appearance of the Mathcad worksheets, so that they resemble the HCM worksheets. It must be emphasized, however, that these background calculations are accessible to the user by simply expanding those portions of the worksheet. If desired, Mathcad allows locking an entire worksheet or regions within it to prevent users from making changes to equations or functions inside the locked regions. Mathcad also provides the tools needed to compile and create electronic books, which are collections of Mathcad worksheets with a table of contents, links and a searchable index.

All of the HCM worksheets were developed using Mathcad 2001i Professional.

Highway Capacity Manual

Mathcad worksheets were developed to perform the computational procedures of five chapters of the Highway Capacity Manual. These chapters were: Signalized Intersections (Chapter 16), Unsignalized Intersections (Chapter 17), Basic Freeway Segments (Chapter 23), Ramps and Ramps Junctions (Chapter 25) and Transit (Chapter 27). The HCM provides worksheets to perform the calculations for the first four of these chapters. For these chapters, an effort was made to maintain the format of the HCM to the extent possible in the Mathcad worksheets. For the Transit chapter, the Mathcad worksheet was developed from scratch to capture the procedures and examples in the chapter.

In some of the HCM worksheets including Signalized Intersections and Ramps and Ramps Junctions, diagrams are used to define input parameters for the procedure. Because this form of input cannot be reproduced in Mathcad, additional tables and variables were introduced in the Mathcad worksheets to input the data. In the HCM worksheets, there are some input tables where letters or expressions are used as input parameters, such as “Yes” or “No”. Mathcad input tables do not allow this type of data. To solve this problem, numbers were used to represent those parameters and footnotes or other annotations were added to the input tables to explain these substitutions. In Mathcad, an input table cannot contain parameters calculated from data that is defined in the same input table. A common example of this situation is the calculation of the hourly flow rate from the volume and peak-hour factor, PHF. In the HCM worksheets the volume and PHF are defined in the same table along with the display of the calculated hourly flow rate. In Mathcad, the flow rate is calculated and displayed separately from the volume and PHF.

The HCM often provides tables from which input values are chosen. In such cases, if the underlying equations were provided, they were implemented in the Mathcad worksheets instead of the tables. When equations were not available, the tables were implemented as matrices with individual values accessed through subscripts.

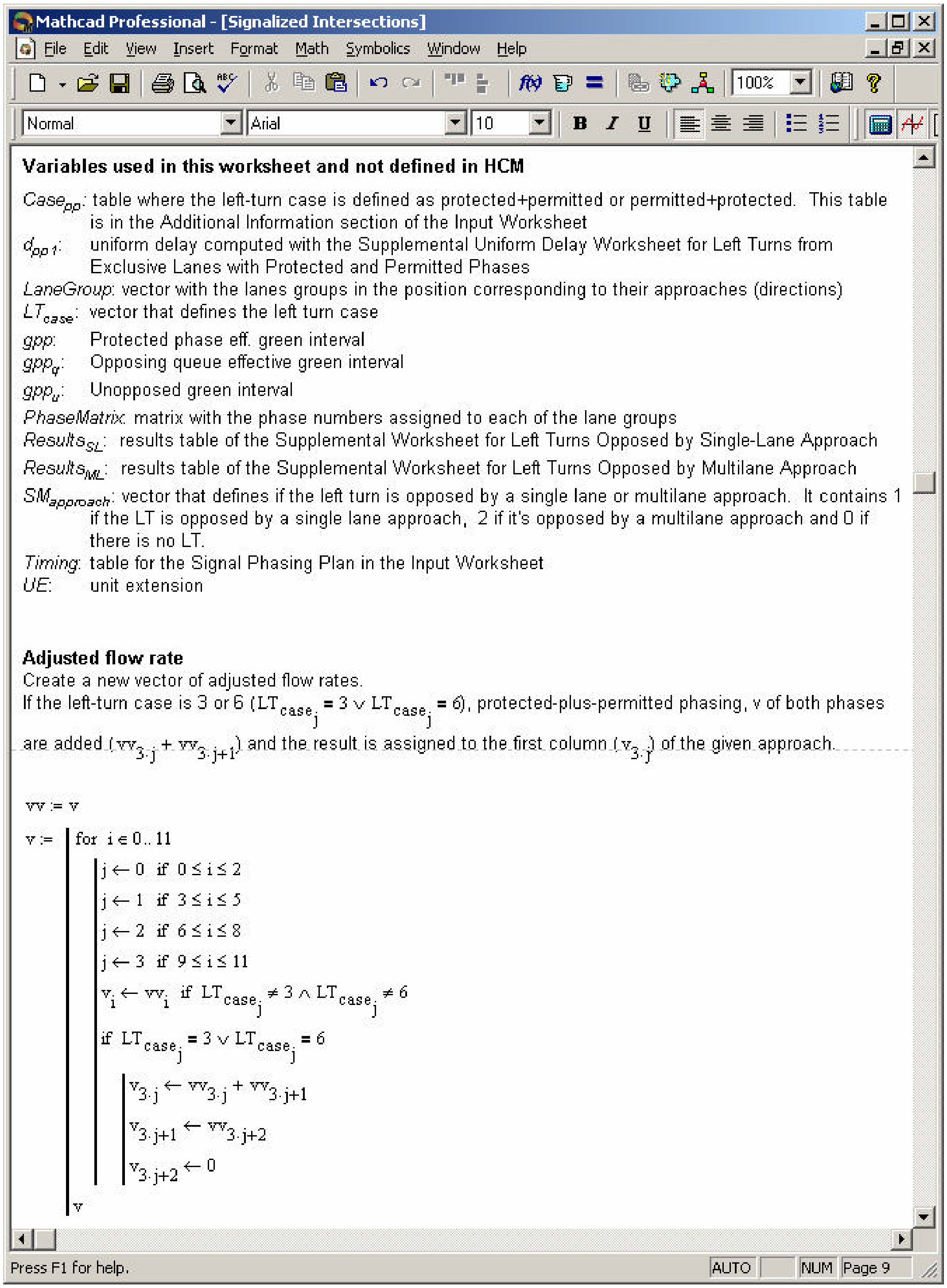
Mathcad does not allow matrices in which elements have different units. In many worksheets, input tables, computational procedures and output tables utilize vectors or matrices composed of data with different units. In these cases, units were not implemented in the Mathcad worksheets. In some HCM worksheets including Basic Freeway Segments, Ramps and Ramps Junctions, and Transit, there are not tables to define the input parameters. For those cases units were implemented in the methodology and new units such as veh (vehicles), pc (passenger car), ln (lane), and I (interchange) had to be defined. This was achieved by defining new dimensionless units in Mathcad.

To validate the Mathcad implementations of the HCM procedures, all of the examples provided for the five chapters of the HCM listed above were computed and the results compared with those of the HCM. In most cases, the results were identical. For a few examples there were slight differences because Mathcad performs all computations with full precision, regardless of how the numbers appear on the worksheet. Conversely, in manual computations with a handheld calculator, the numbers are typically rounded in each step of the calculations. This can lead to different results, particularly in cases where computations involve five or more significant figures as in the AWSC Unsignalized Intersections worksheet.

All of the procedures and equations implemented in the Mathcad worksheets are annotated with text that explains what they do and how they work. There is also a description of every new variable introduced in the Mathcad worksheet. This facilitates later review and modification of the procedures or equations. An example of these annotations is shown in Figure 2. Mathcad built-in functions were also used in some of the procedures; a description of the functions can be accessed through the Mathcad help menu.

One of the limitations of some existing software implementations of the HCM methodologies is that the user is not allowed to access equations or procedures used in the calculation process. The user must rely on the accuracy of the output results. In the Mathcad worksheets, the HCM methodologies implemented are completely accessible to the user. All equations, tables and assumptions used in the calculation process are referenced to the HCM, facilitating their review and modification. This feature of the Mathcad worksheets gives the user complete control of the computation process, allowing the user to explore the sensitivity of results to changes in the input parameters or in the computational algorithms, varying equations or values in the exhibits.

Challenges associated with the implementation of individual HCM chapters and changes and additions made to the format of the HCM worksheets, reflecting the capabilities and limitations of Mathcad, are discussed in the following chapters.



Mathcad Professional - [Signalized Intersections]

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Variables used in this worksheet and not defined in HCM

Case$_{pp}$: table where the left-turn case is defined as protected+permitted or permitted+protected. This table is in the Additional Information section of the Input Worksheet

d_{pp1}: uniform delay computed with the Supplemental Uniform Delay Worksheet for Left Turns from Exclusive Lanes with Protected and Permitted Phases

LaneGroup: vector with the lanes groups in the position corresponding to their approaches (directions)

LT_{case}: vector that defines the left turn case

gpp: Protected phase eff. green interval

gpp_q: Opposing queue effective green interval

gpp_u: Unopposed green interval

PhaseMatrix: matrix with the phase numbers assigned to each of the lane groups

Results$_{SL}$: results table of the Supplemental Worksheet for Left Turns Opposed by Single-Lane Approach

Results$_{ML}$: results table of the Supplemental Worksheet for Left Turns Opposed by Multilane Approach

$SM_{approach}$: vector that defines if the left turn is opposed by a single lane or multilane approach. It contains 1 if the LT is opposed by a single lane approach, 2 if it's opposed by a multilane approach and 0 if there is no LT.

Timing: table for the Signal Phasing Plan in the Input Worksheet

UE: unit extension

Adjusted flow rate

Create a new vector of adjusted flow rates.

If the left-turn case is 3 or 6 ($LT_{case_j} = 3 \vee LT_{case_j} = 6$), protected-plus-permitted phasing, v of both phases are added ($vv_{3\cdot j} + vv_{3\cdot j+1}$) and the result is assigned to the first column ($v_{3\cdot j}$) of the given approach.

$vv := v$

$$
v := \left|
\begin{array}{l}
\text{for } i \in 0..11 \\
\quad \left|
\begin{array}{l}
j \leftarrow 0 \ \text{ if } 0 \le i \le 2 \\
j \leftarrow 1 \ \text{ if } 3 \le i \le 5 \\
j \leftarrow 2 \ \text{ if } 6 \le i \le 8 \\
j \leftarrow 3 \ \text{ if } 9 \le i \le 11 \\
v_i \leftarrow vv_i \ \text{ if } LT_{case_j} \ne 3 \wedge LT_{case_j} \ne 6 \\
\text{if } LT_{case_j} = 3 \vee LT_{case_j} = 6 \\
\quad \left|
\begin{array}{l}
v_{3\cdot j} \leftarrow vv_{3\cdot j} + vv_{3\cdot j+1} \\
v_{3\cdot j+1} \leftarrow vv_{3\cdot j+2} \\
v_{3\cdot j+2} \leftarrow 0
\end{array}
\right.
\end{array}
\right. \\
v
\end{array}
\right.
$$

Press F1 for help. AUTO NUM Page 9

Figure 2. Example of annotations in the Mathcad worksheets

CHAPTER 2

SIGNALIZED INTERSECTIONS

The format of the Mathcad worksheets developed for this chapter is very similar to the HCM worksheets, except for two differences in the Input worksheet. In the HCM Input Worksheet, a diagram of the intersection is used to define the intersection geometry. Because Mathcad is not capable of using such diagrams to input data, two tables were introduced to define the intersection geometry as shown in Figure 3.

The signal phasing plan in the HCM worksheet is defined using arrows that indicate the approach and movement involved in each phase and whether the turns are protected or permitted. The same approach is used to assign lanes for each approach and movement. To define signal phasing and lane groups in the Mathcad worksheet, the two tables shown in Figure 4 are used. In the first table, a lane group number is assigned to each movement for every approach. In the second table, a signal phase number is assigned to each lane group defined in the first table. The number is positive if the left turn is protected or negative if the left turn is permitted (Elena Prassas and George List, personal communication). The lane group numbers along with the signs of the signal phase are used to identify the columns in the Volume Adjustment and Saturation Flow Rate worksheet and in the Capacity and LOS worksheet, replacing the arrows used in the HCM worksheets. An extra column was added to the lane group table to define the initial queue at the start of the analysis period, Q_b, for each lane group. Figure 4 also shows the additional table used to define the unit extension for each phase of the signal phasing plan.

The minimum pedestrian green time, G_p, appears in the Volume and Timing Input section in the Input Worksheet of HCM. In the Mathcad worksheet, G_p is displayed in a different table after the Signal Phasing Plan section. There are two reasons for this change: first, G_p is a calculated parameter and cannot be displayed in an input table along with input parameters; second, the cycle length, C, is needed to compute G_p, and therefore G_p can only be calculated and displayed after C is defined due to the computation flow used by Mathcad.

The variables that were added to the Input worksheet are base saturation flow rate (s_O), passenger-car equivalent (E_T), adjustment factor for lane utilization (f_{LU}), for every approach, duration of analysis period (T), and the incremental delay adjustment factor, I.

Another change made to the HCM worksheets was the elimination of the input section from the Supplemental Worksheets for Permitted Left Turns Opposed by Single-Lane and Multilane Approaches. All the parameters of those sections are calculated from the data introduced in the Input Worksheet.

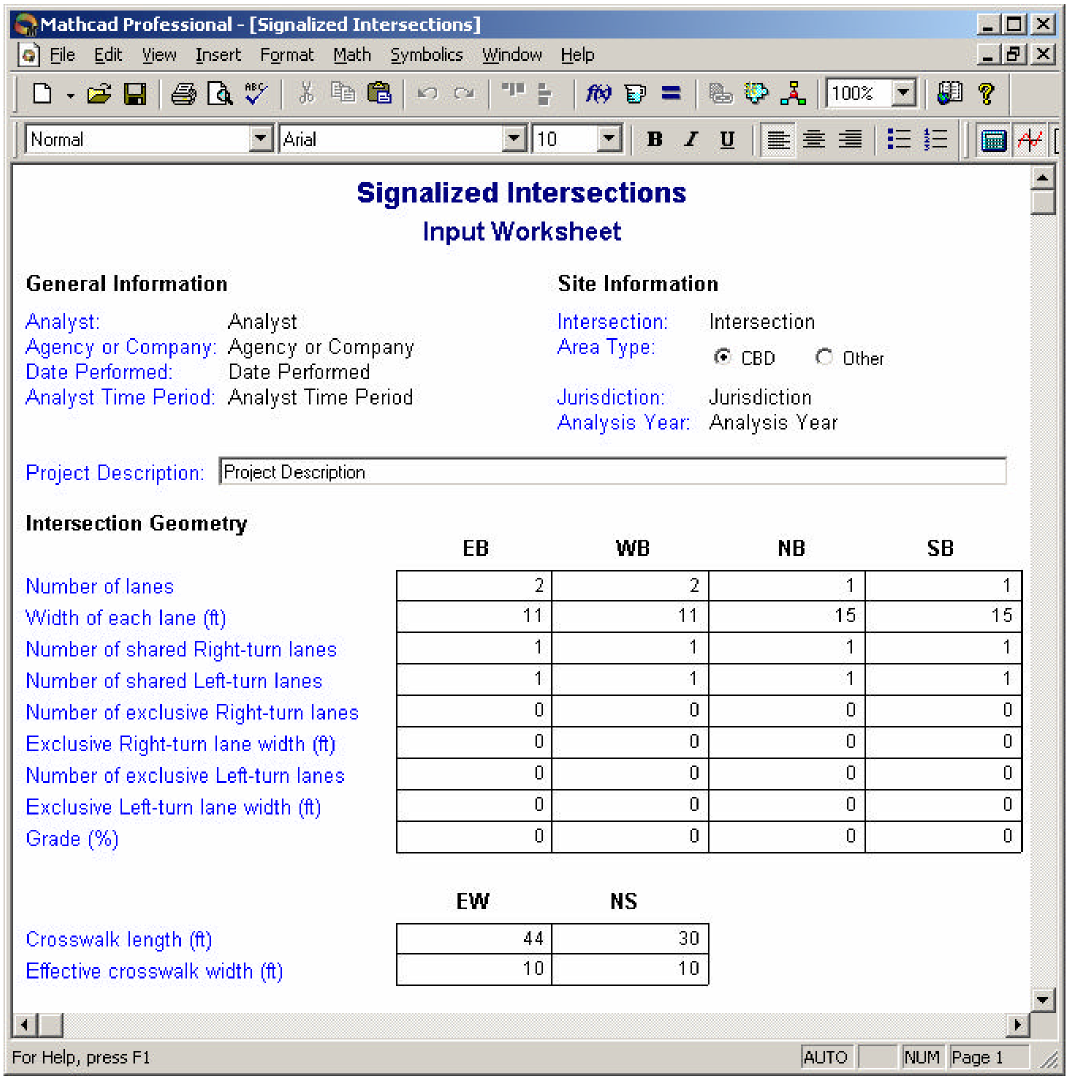
Example 2.1 (Example Problem 1, Chapter 16 - Signalized Intersections, HCM (2,000))

The intersection: the intersection is located in the central business district (CBD) of a small urban area. Intersection geometry and flow characteristics are shown in Figures 5 and 6.

The question: what are the delay and peak-hour LOS of this intersection?

The facts: the facts are shown in Figures 5, 6 and 7.

- EB and WB HV = 5%
- NB and SB HV = 8%
- PHF = 0.90
- Two-phase signal
- NB-SB green = 36 s
- EB-WB green = 26 s
- Yellow = 4 s
- No parking at the intersection
- Pedestrian volume = 100 p/h
- Bicycle volume = 20 bicycles/h
- Movement lost time = 4 s
- Level terrain



Mathcad Professional - [Signalized Intersections]

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Signalized Intersections

Input Worksheet

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analyst Time Period: Analyst Time Period

Site Information

Intersection: Intersection
Area Type: CBD Other
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year

Project Description: Project Description

Intersection Geometry

	EB	WB	NB	SB
Number of lanes	2	2	1	1
Width of each lane (ft)	11	11	15	15
Number of shared Right-turn lanes	1	1	1	1
Number of shared Left-turn lanes	1	1	1	1
Number of exclusive Right-turn lanes	0	0	0	0
Exclusive Right-turn lane width (ft)	0	0	0	0
Number of exclusive Left-turn lanes	0	0	0	0
Exclusive Left-turn lane width (ft)	0	0	0	0
Grade (%)	0	0	0	0

	EW	NS
Crosswalk length (ft)	44	30
Effective crosswalk width (ft)	10	10

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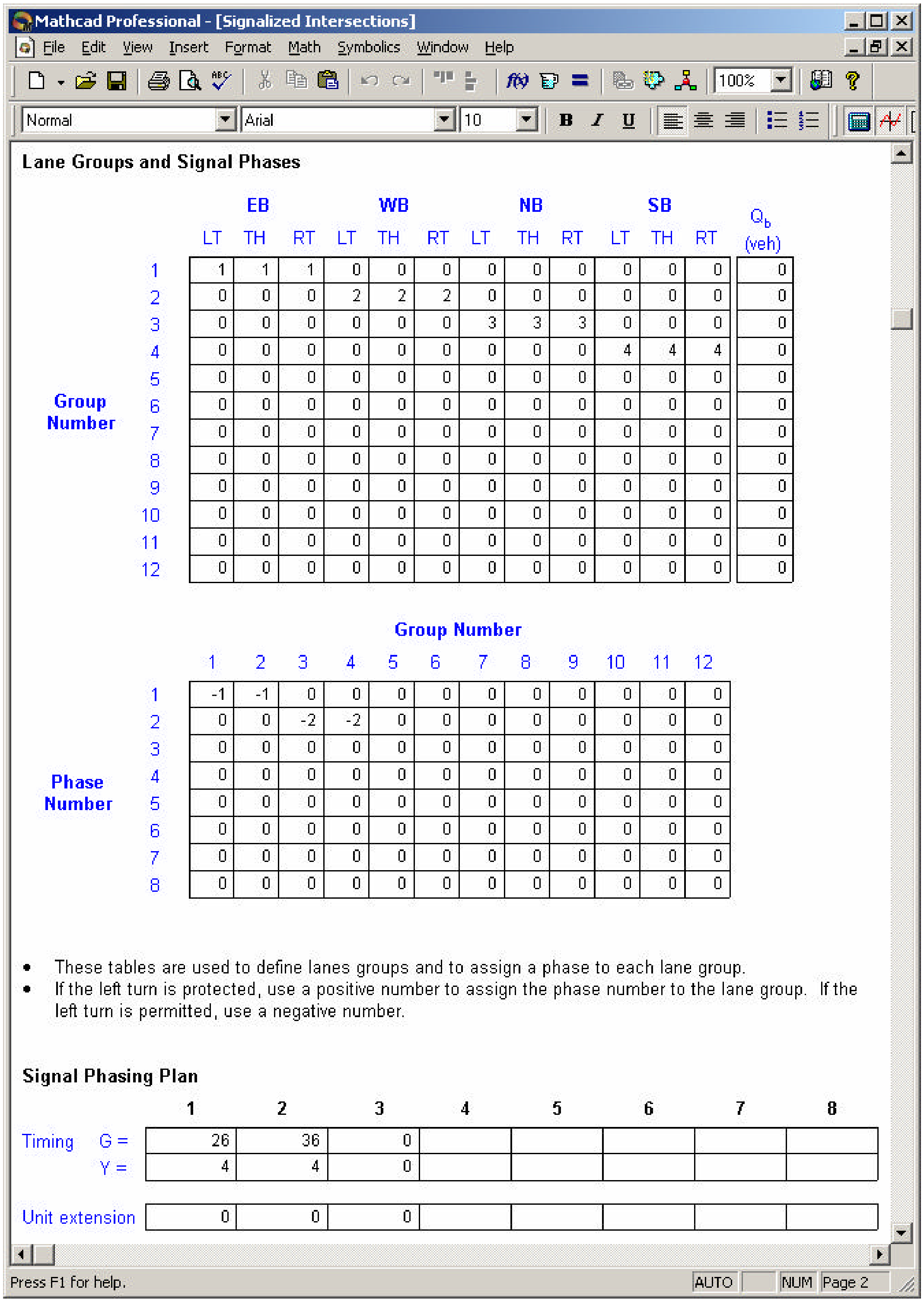
Figure 3. Input tables for the intersection geometry in the Signalized Intersections worksheet



Lane Groups and Signal Phases

Group Number

	EB LT	EB TH	EB RT	WB LT	WB TH	WB RT	NB LT	NB TH	NB RT	SB LT	SB TH	SB RT	Q_b (veh)
1	1	1	1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	2	2	2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	3	3	3	0	0	0	0
4	0	0	0	0	0	0	0	0	0	4	4	4	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0

Group Number

Phase Number	1	2	3	4	5	6	7	8	9	10	11	12
1	-1	-1	0	0	0	0	0	0	0	0	0	0
2	0	0	-2	-2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0

- These tables are used to define lanes groups and to assign a phase to each lane group.
- If the left turn is protected, use a positive number to assign the phase number to the lane group. If the left turn is permitted, use a negative number.

Signal Phasing Plan

		1	2	3	4	5	6	7	8
Timing	G =	26	36	0					
	Y =	4	4	0					
Unit extension		0	0	0					

Figure 4. Tables to assign lane groups and signal phases in the Signalized Intersections worksheet

Comments: these comments are shown in Figure 5, 6 and 7.

- Assume crosswalk width = 10 ft for all approaches
- Assume base saturation flow rate = 1,900 pc/h/ln
- Assume ET = 2.0
- No buses
- 70.0 s cycle length, with green times given

Solution: the solution to the example is shown from Figure 8 to Figure 13.

The output results computed by the Mathcad worksheets compares very well with those shown in the example of the Highway Capacity Manual. As discussed in Chapter 1, there are slight differences because Mathcad performs all computations with full precision and conversely, in manual computations the numbers are usually rounded in each step of the calculations.

Signalized Intersections
Input Worksheet

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analyst Time Period: Analyst Time Period

Site Information

Intersection: Intersection
Area Type: ◉ CBD ○ Other
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year

Project Description: Example

Intersection Geometry

	EB	WB	NB	SB
Number of lanes	2	2	1	1
Width of each lane (ft)	11	11	15	15
Number of shared Right-turn lanes	1	1	1	1
Number of shared Left-turn lanes	1	1	1	1
Number of exclusive Right-turn lanes	0	0	0	0
Exclusive Right-turn lane width (ft)	0	0	0	0
Number of exclusive Left-turn lanes	0	0	0	0
Exclusive Left-turn lane width (ft)	0	0	0	0
Grade (%)	0	0	0	0

	EW	NS
Crosswalk length (ft)	44	30
Effective crosswalk width (ft)	10	10

Volume and Timing Input

	EB			WB			NB			SB		
	LT	TH	RT[1]	LT	TH	RT[1]	LT	TH	RT[1]	LT	TH	RT[1]
Volume, V (veh/h)	65	620	35	30	700	20	30	370	20	40	510	50
% heavy vehicles, %HV	5	5	5	5	5	5	8	8	8	8	8	8
Peak-hour factor, PHF	0	0.9	0	0	0.9	0	0	0.9	0	0	0.9	0
Pretimed (1) or actuated (2)	0	1	0	0	1	0	0	1	0	0	1	0
Start-up time, l_1 (s)	0	0	0	0	0	0	0	0	0	0	0	0
Extension of effective green time, e (s)	0	0	0	0	0	0	0	0	0	0	0	0
Arrival Type, AT	0	4	0	0	2	0	0	3	0	0	3	0

	EB	WB	NB	SB
Approach pedestrian volume, V_{ped} (p/h)	100	100	100	100
Approach bicycle volume, V_{bic} (bicycles/h)	20	20	20	20
Parking, Yes (1) or No (2)	2	2	2	2
Parking maneuvers, N_m (maneuvers/h)	0	0	0	0
Bus stopping, N_b (buses/h)	0	0	0	0

Note: [1] RT volumes exclude RTOR

Figure 5. Example 2.1 - Input Worksheet

Lane Group and Signal Phases

Group Number	EB LT	EB TH	EB RT	WB LT	WB TH	WB RT	NB LT	NB TH	NB RT	SB LT	SB TH	SB RT	Q_b (veh)
1	1	1	1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	2	2	2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	3	3	3	0	0	0	0
4	0	0	0	0	0	0	0	0	0	4	4	4	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0

Group Number

Phase Number	1	2	3	4	5	6	7	8	9	10	11	12
1	-1	-1	0	0	0	0	0	0	0	0	0	0
2	0	0	-2	-2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0

- These tables are used to define lanes groups and to assign a phase to each lane group.
- If the left turn is protected, use a positive number to assign the phase number to the lane group. If the left turn is permitted, use a negative number.

Signal Phasing Plan

		1	2	3	4	5	6	7	8
Timing	G =	26	36	0					
	Y =	4	4	0					
Unit extension		0	0	0					

The table for the unit extension assignment is additional to the HCM Input Worksheet. The unit extension is used to compute the Incremental Delay Calibration Factor, k.

Cycle length C = 70 s

Figure 6. Example 2.1 - Input Worksheet (contd.)

	EB	WB	NB	SB
Min. timing for pedestrians, G_p (s)	11.2	11.2	14.7	14.7

$G_p^T =$

Additional Information

Information needed to perform some computations and that is not defined in the HCM Input Worksheet.

Base saturation flow rate (pc/h/ln) $s_0 := 1900$

Passenger-car equivalent (pc/HV) $E_T := 2$

Lane Utilization Adjustment Factor

	EB	WB	NB	SB
Lane utilization factor	0.95	0.95	1	1

Control Delay

Duration of analysis period (h) $T := 0.25$

Upstream filtering metering adjustment factor $I := 1$

Figure 7. Example 2.1 - Input Worksheet (contd.)

Supplemental Worksheet for Permitted Left Turns Opposed by Single-Lane Approach

General Information

Project Description: PD = "Example "

Computation

	EB	WB	NB	SB
Total actual green time for LT lane group, G(s)	0	0	36	36
Effective permitted green time for LT lane group, g(s)	0	0	36	36
Opposing effective green time, g_0 (s)	0	0	36	36
Number of lanes in LT lane group, N	0	0	1	1
Adjusted LT flow rate, v_{LT} (veh/h)	0	0	33	44
Proportion of LT volume in LT lane group, P_{LT}	0	0	0.071	0.066
Proportion of LT volume in opposing flow, P_{LTo}	0	0	0.066	0.071
Adjusted flow rate for opposing approach, v_o (veh/h)	0	0	667	466
Lost time for LT lane group, t_L	0	0	4	4
LT (left turns) volume per cycle, LTC	0	0	0.642	0.856
Opposing flow per lane, per cycle, v_{olc} (veh/C/ln)	0	0	12.969	9.061
Opposing platoon ratio, R_{po}	0	0	1	1
Portion of green time, TH veh not be blocked by LT veh. g_f (s)	0	0	14.783	12.509
Opposing queue ratio, q_{ro}	0	0	0.486	0.486
Portion of green time blocked by a queue of opp. veh, g_q (s)	0	0	12.191	8.32
Portion of green time not block. by a queue of opp. veh. g_u (s)	0	0	21.217	23.491
Max num of opp. veh. that could arrive during g_{diff}, n	0	0	0	0
Proportion of TH and RT vehicles, P_{THo}	0	0	0.934	0.929
Through-car equiv. for permitted LT, E_{L1}	0	0	2.7	2.2
Through-car equiv. for opp. mov. of permitted LT, E_{L2}	0	0	1	1
Minimum left-turn adjustment factor, f_{min}	0	0	0.059	0.059
Max(g_q - g_f, 0), g_{diff}	0	0	0	0
Left-turn adjustment factor, f_{LT}	0	0	0.937	0.952

$Results_{SL}$ =

Figure 8. Example 2.1 - Supplemental Worksheet for Permitted Left Turns Opposed by Single-Lane Approach

Supplemental Worksheet for Permitted Left Turns Opposed by Multilane Approach

General Information

Project Description: PD = "Example "

Computation

	EB	WB	NB	SB
Total actual green time for LT lane group, G(s)	26	26	0	0
Effective permitted green time for LT lane group, g(s)	26	26	0	0
Opposing effective green time, g_o (s)	26	26	0	0
Number of lanes in LT lane group, N	2	2	0	0
Number of lanes in opposing approach, N_o	2	2	0	0
Adjusted LT flow rate, v_{LT} (veh/h)	72	33	0	0
Proportion of LT volume in LT lane group, P_{LT}	0.09	0.04	0	0
Adjusted flow rate for opposing approach, v_o (veh/h)	833	800	0	0
Lost time for LT lane group, t_L	4	4	0	0
LT (left turn) volume per cycle, LTC	1.4	0.642	0	0
Opposing lane utilization factor, f_{LUo}	0.95	0.95	0	0
Opposing flow per lane, per cycle, v_{olc} (veh/C/ln)	8.525	8.187	0	0
Portion of green time, TH veh not be blocked by LT veh. g_f (s)	4.461	9.687	0	0
Opposing platoon ratio, R_{po}	0.667	1.333	0	0
Opposing queue ratio, q_{ro}	0.752	0.505	0	0
Portion of green time blocked by a queue of opp. veh, g_q (s)	11.314	8.013	0	0
Portion of green time not block. by a queue of opp. veh. g_u (s)	14.686	16.313	0	0
Through-car equiv. for permitted LT, E_{L1}	3.3	3.2	0	0
Proportion of left turns in shared lane, P_L	0.268	0.094	0	0
Minimum left-turn adjustment factor, f_{min}	0.098	0.084	0	0
LT adjust. factor applied only to left-turn lane, f_m	0.521	0.893	0	0
Left-turn adjustment factor, f_{LT}	0.716	0.901	0	0

$Results_{ML}$ =

Figure 9. Example 2.1 - Supplemental Worksheet for Permitted Left Turns Opposed by Multilane Approach

Supplemental Worksheet for Pedestrian-Bicycle Effects On Permitted Left Turns and Right Turns

General Information

Project Description: PD = "Example "

Permitted Left Turns

	EB	WB	NB	SB
Effective pedestrian green time, g_p (s)	26	26	36	36
Conflicting pedestrian volume, v_{ped} (p/h)	100	100	100	100
Pedestrian flow rate, v_{pedg}	269	269	194	194
Average pedestrian occupancy, OCC_{pedg}	0.135	0.135	0.097	0.097
Opposing queue clearing time, g_q (s)	11.314	8.013	12.191	8.32
Effec. pedes. green consumed by oppos. veh. queue	0.435	0.308	0.339	0.231
Pedestrian occupancy after the opposing queue clears	0.105	0.114	0.081	0.086
Opposing flow rate, v_o (veh/h)	833	800	667	466
Relevant occupancy, OCC_r	0.033	0.037	0.032	0.045
Number of cross-street receiving lanes, N_{rec}	1	1	2	2
Number of turning lanes, N_{turn}	1	1	1	1
Permitted phase adjust. pedes./bicycle blockage, A_{pbT}	0.967	0.963	0.981	0.973
Proportion of left turns, P_{LT}	0.09	0.04	0.071	0.066
Proportion of left turns using protected phase, P_{LTA}	0	0	0	0
Pedestrian adjustment factor, f_{Lpb}	0.997	0.999	0.999	0.998

$Results_{PBLT}$ =

Permitted Right Turns

	EB	WB	NB	SB
Effective pedestrian green time, g_p (s)	26	26	36	36
Conflicting pedestrian volume, v_{ped} (p/h)	100	100	100	100
Conflicting bicycle volume, v_{bic} (bicycles/h)	20	20	20	20
Pedestrian flow rate, v_{pedg}	269	269	194	194
Average pedestrian occupancy, OCC_{pedg}	0.135	0.135	0.097	0.097
Effective green, g (s)	26	26	36	36
Bicycle flow rate, v_{bicg}	54	54	39	39
Bicycle conflict zone occupancy, OCC_{bicg}	0.04	0.04	0.034	0.034
Relevant occupancy, OCC_r	0.169	0.169	0.128	0.128
Number of cross-street receiving lanes, N_{rec}	1	1	2	2
Number of turning lanes, N_{turn}	1	1	1	1
Permitted phase adjust. pedes./bicycle blockage, A_{pbT}	0.831	0.831	0.923	0.923
Proportion of right turns, P_{RT}	0.049	0.026	0.047	0.084
Proportion of right turns using protected phase P_{RTA}	0	0	0	0
Pedestrian-bicycle adjustment factor, f_{Rpb}	0.992	0.996	0.996	0.994

$Results_{PBRT}$ =

Figure 10. Example 2.1 - Supplemental Worksheet for Pedestrian-Bicycle Effects on Permitted Left Turns and Right Turns

Volume Adjustment and Saturation Flow Rate Worksheet

General Information

Project Description: PD = "Example "

Volume Adjustment

	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Volume, V (veh/h)	65	620	35	30	700	20	30	370	20	40	510	50
Peak-hour factor, PHF	0	0.9	0	0	0.9	0	0	0.9	0	0	0.9	0
Adjusted flow rate, v_p=V/PHF (veh/h)	72	689	39	33	778	22	33	411	22	44	567	56
Lane Group	0	-1	0	0	-2	0	0	-3	0	0	-4	0
Adjusted flow rate in lane group, v (veh/h)	0	800	0	0	833	0	0	466	0	0	667	0
Proportion of LT or RT (P_{LT} or P_{RT})	0.09	0	0.049	0.04	0	0.026	0.071	0	0.047	0.066	0	0.084

$Results_{VA}$ =

Saturation Flow Rate (*see Exhibit 16-7 to determine adjustment factors*)

	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Lane Group	0	-1	0	0	-2	0	0	-3	0	0	-4	0
Base saturation flow, s_o (pc/h/ln)	0	1900	0	0	1900	0	0	1900	0	0	1900	0
Number of lanes, N	0	2	0	0	2	0	0	1	0	0	1	0
Lane width adjustment factor, f_w	0	0.967	0	0	0.967	0	0	1.1	0	0	1.1	0
Heavy-vehicle adjustment factor, f_{HV}	0	0.952	0	0	0.952	0	0	0.926	0	0	0.926	0
Grade adjustment factor, f_g	0	1	0	0	1	0	0	1	0	0	1	0
Parking adjustment factor, f_p	0	1	0	0	1	0	0	1	0	0	1	0
Bus blockage adjustment factor, f_{bb}	0	1	0	0	1	0	0	1	0	0	1	0
Area type adjustment factor, f_a	0	0.9	0	0	0.9	0	0	0.9	0	0	0.9	0
Lane utilization adjustment factor, f_{LU}	0	0.95	0	0	0.95	0	0	1	0	0	1	0
Left-turn adjustment factor, f_{LT}	0	0.716	0	0	0.901	0	0	0.937	0	0	0.952	0
Right-turn adjustment factor, f_{RT}	0	0.993	0	0	0.996	0	0	0.994	0	0	0.989	0
Left-turn ped/bike adjust. factor, f_{Lpb}	0	0.997	0	0	0.999	0	0	0.999	0	0	0.998	0
Right-turn ped/bike adjust. factor, f_{Rpb}	0	0.992	0	0	0.996	0	0	0.996	0	0	0.994	0
Adjusted saturation flow, s (veh/h)	0	2101	0	0	2669	0	0	1613	0	0	1626	0

$Results_{SFR}$ =

Figure 11. Example 2.1 - Volume Adjustment and Saturation Flow Rate Worksheet

Capacity and LOS Worksheet

General Information

Project Description: PD = "Example "

Capacity Analysis

Phase number	1	1	2	2
Lane group	-1	-2	-3	-4
Adjusted flow rate, v (veh/h)	800	833	466	667
Saturation flow rate, s (veh/h)	2101	2669	1613	1626
Lost time, t_L (s)	4	4	4	4
Effective green time, g(s)	26	26	36	36
Green ratio, g/C	0.371	0.371	0.514	0.514
Lane group capacity, c (veh/h)	780	991	830	836
v/c ratio, X	1.026	0.841	0.561	0.798
Flow ratio, v/s	0.381	0	0	0.41
Critical lane group/phase (1)	1	0	0	1

ResultsCapacity =

Sum of flow ratios for critical lanes groups: $Y_c = 0.791$

Total lost time per cycle: $L = 8$ s

Critical flow rate to capacity ratio: $X_c = 0.893$

Lane Group Capacity, Control Delay, and LOS Determination

	EB			WB			NB			SB		
Lane group	0	1	0	0	2	0	0	3	0	0	4	0
Adjusted flow rate, v (veh/h)	0	800	0	0	833	0	0	466	0	0	667	0
Lane group capacity, c (veh/h)	0	780	0	0	991	0	0	830	0	0	836	0
v/c ratio, X	0	1.026	0	0	0.841	0	0	0.561	0	0	0.798	0
Total green ratio, g/C	0	0.371	0	0	0.371	0	0	0.514	0	0	0.514	0
Uniform delay, d_1 (s/veh)	0	22	0	0	20.106	0	0	11.609	0	0	14.003	0
Incremental delay calibration, k	0	0.5	0	0	0.5	0	0	0.5	0	0	0.5	0
Incremental delay, d_2 (s/veh)	0	38.911	0	0	8.556	0	0	2.738	0	0	7.825	0
Initial queue delay, d_3 (s/veh)	0	0	0	0	0	0	0	0	0	0	0	0
Progression adjustment factor, PF	0	0.924	0	0	1.113	0	0	1	0	0	1	0
Delay, d (s/veh)	0	59.2	0	0	30.9	0	0	14.3	0	0	21.8	0
LOS by lane group	0	"E"	0	0	"C"	0	0	"B"	0	0	"C"	0

LOS_1 =

Delay by approach, d_A (s/veh)	59.2	30.9	14.3	21.8
LOS by approach	"E"	"C"	"B"	"C"
Approach flow rate, v_A (veh/h)	800	833	466	667

LOS_2 =

Intersection delay (s/veh) $d_I = 34.1$

Intersection LOS LOS_I = "C"

Figure 12. Example 2.1 - Capacity and LOS Worksheet

Supplemental Uniform Delay Worksheet for Left Turns from Exclusive Lanes with Protected and Permitted Phases

General Information

Project Description: PD = "Example "

v/c Ratio Computation

	EB	WB	NB	SB
Protected phase effective green interval, g (s)	0	0	0	0
Opposing queue effective green interval, g_q (s)	0	0	0	0
Unopposed green interval, g_u (s)	0	0	0	0
Red time, r(s)	0	0	0	0
Arrival rate, q_a (veh/s)	0	0	0	0
Protected phase departure, s_p (veh/s)	0	0	0	0
Permitted phase departure, s_s (veh/s)	0	0	0	0
v/c ratio, X_{perm}	0	0	0	0
v/c ratio, X_{prot}	0	0	0	0

$Results_{vcratio}$ =

Uniform Queue Size and Delay Computations

	EB	WB	NB	SB
Queue at beginning of green arrow, Q_a	0	0	0	0
Queue at beginning of unsaturated green, Q_u	0	0	0	0
Residual queue, Q_r	0	0	0	0
Uniform delay, d_1	0	0	0	0

$Results_{delay}$ =

Figure 13. Example 2.1 - Supplemental Uniform Delay Worksheet for Left Turns from Exclusive Lanes with Protected and Permitted Phases

CHAPTER 3

UNSIGNALIZED INTERSECTIONS

Two-way stop-controlled intersection (TWSC)

The Geometrics and Movements section in Worksheet 1 of the HCM shows two diagrams of the intersection. One is used as a reference that shows all 16 possible movements. The other diagram shows the movements and volumes present in the actual intersection. The latter was eliminated from the Mathcad worksheet and only the reference diagram was included as shown in Figure 14. Figure 15 shows two sections of Worksheet 2 where the output parameters, the hourly flow rate v_h and percent of blockage f_p, are displayed separately from the input parameters for the reason described previously.

Worksheet 5c shown in Figure 16 displays the proportion for minor movements, p_x, calculated by the Mathcad worksheet. A new table was introduced to allow the user to change the values of p_x calculated by the worksheet. These new values are used in subsequent calculations rather than the values computed by Mathcad. (George List, personal communication)

The remainder of the TWSC worksheets is essentially the same as the HCM worksheets.

All-way stop-controlled intersection (AWSC)

This worksheet contains the most complex calculations of the five chapters that were implemented due to the iterative nature of the procedure to compute the final results. The Geometrics and Movements section in Worksheet 1 of the HCM contains two diagrams of the intersection that are similar to the TWSC intersection worksheet. One is a reference that shows all 12 possible movements, and the other shows the

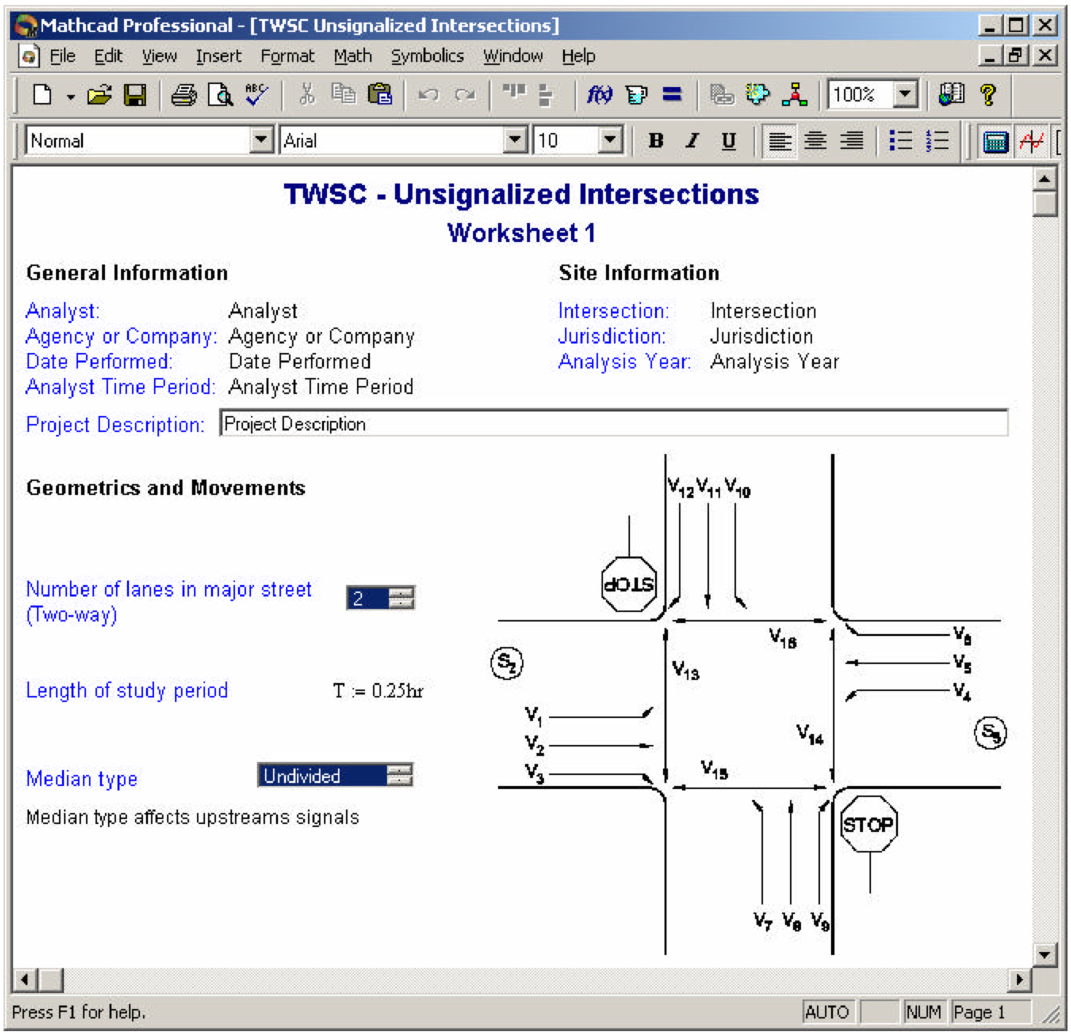
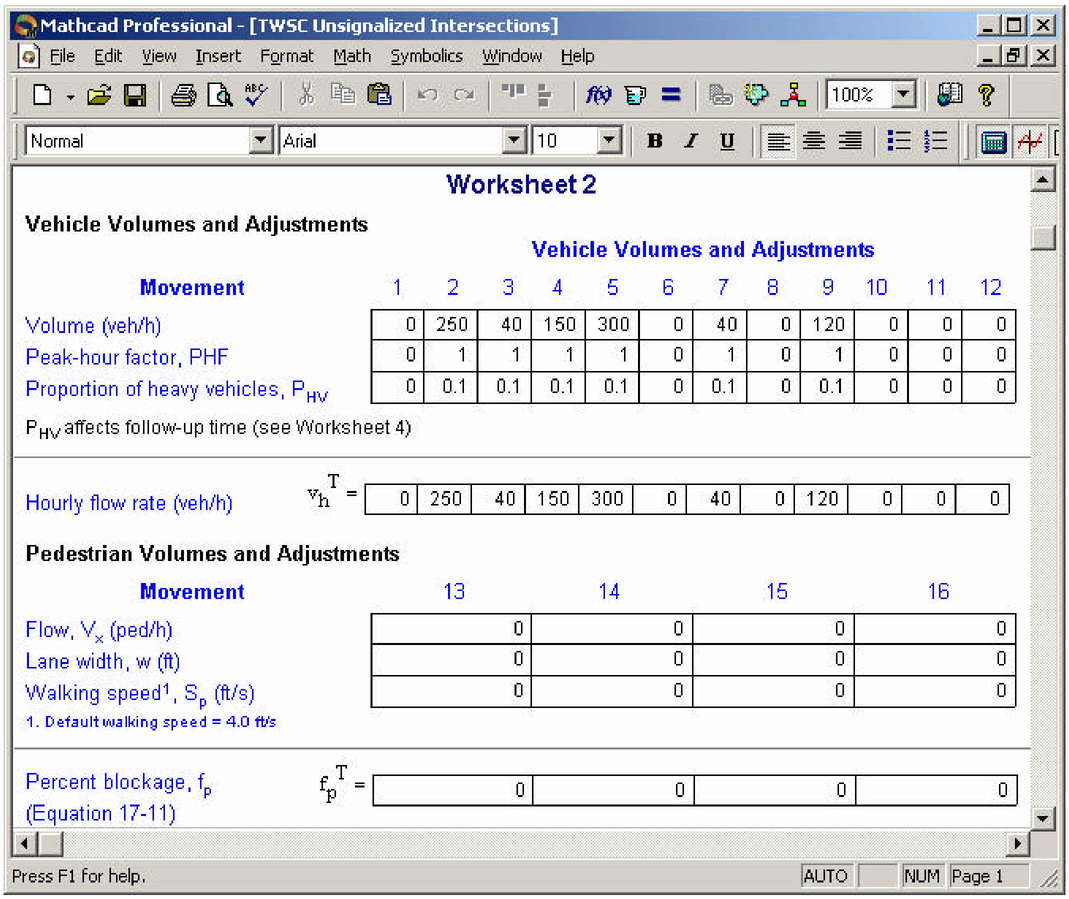


Figure 14. Worksheet 1 of TWSC – Unsignalized Intersections



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Worksheet 2

Vehicle Volumes and Adjustments

Vehicle Volumes and Adjustments

Movement	1	2	3	4	5	6	7	8	9	10	11	12
Volume (veh/h)	0	250	40	150	300	0	40	0	120	0	0	0
Peak-hour factor, PHF	0	1	1	1	1	0	1	0	1	0	0	0
Proportion of heavy vehicles, P_{HV}	0	0.1	0.1	0.1	0.1	0	0.1	0	0.1	0	0	0

P_{HV} affects follow-up time (see Worksheet 4)

Hourly flow rate (veh/h) $v_h^T =$

0	250	40	150	300	0	40	0	120	0	0	0

Pedestrian Volumes and Adjustments

Movement	13	14	15	16
Flow, V_x (ped/h)	0	0	0	0
Lane width, w (ft)	0	0	0	0
Walking speed[1], S_p (ft/s)	0	0	0	0

1. Default walking speed = 4.0 ft/s

Percent blockage, f_p (Equation 17-11) $f_p^T =$

0	0	0	0

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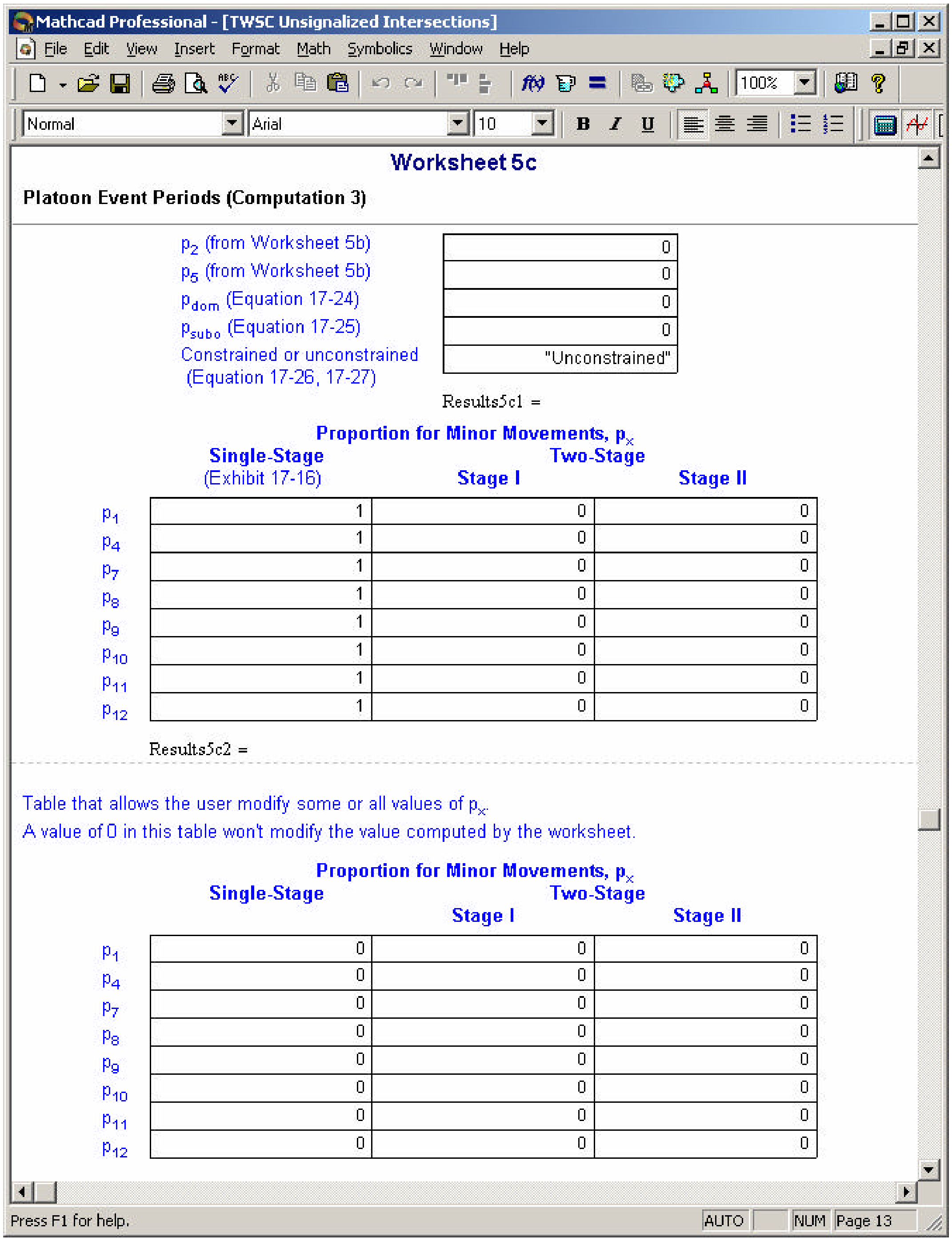
Figure 15. Worksheet 2 of TWSC – Unsignalized Intersections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Worksheet 5c

Platoon Event Periods (Computation 3)

p_2 (from Worksheet 5b)	0
p_5 (from Worksheet 5b)	0
p_{dom} (Equation 17-24)	0
p_{subo} (Equation 17-25)	0
Constrained or unconstrained (Equation 17-26, 17-27)	"Unconstrained"

Results5c1 =

Proportion for Minor Movements, p_x

	Single-Stage (Exhibit 17-16)	**Two-Stage** **Stage I**	**Stage II**
p_1	1	0	0
p_4	1	0	0
p_7	1	0	0
p_8	1	0	0
p_9	1	0	0
p_{10}	1	0	0
p_{11}	1	0	0
p_{12}	1	0	0

Results5c2 =

Table that allows the user modify some or all values of p_x.
A value of 0 in this table won't modify the value computed by the worksheet.

Proportion for Minor Movements, p_x

	Single-Stage	**Two-Stage** **Stage I**	**Stage II**
p_1	0	0	0
p_4	0	0	0
p_7	0	0	0
p_8	0	0	0
p_9	0	0	0
p_{10}	0	0	0
p_{11}	0	0	0
p_{12}	0	0	0

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Figure 16. Worksheet 5c of TWSC – Unsignalized Intersections

movements and volumes present in the actual intersection. Only the reference diagram was implemented as explained previously for the TWSC intersection worksheet.

Figure 17 shows the Volume Adjustments and Lane Assignments section in Worksheet 2, where the input and output parameters are defined and displayed in separate tables. Figure 17 also shows the list boxes that were implemented to define the Geometry Group for each approach on the Volume Adjustments and Lane Assignments section in Worksheet 2. The list boxes allow the user select 0 if the approach is not present on the intersection or any of the eight groups (1, 2, 3a, 3b, 4a, 4b, 5 and 6) defined in the HCM.

To evaluate the departure headway, h_d, in Worksheet 4a, a maximum of five iterations were specified in the Mathcad procedure to match the number of iterations specified in the HCM worksheet. However, the number of iterations can be easily increased by the user if desired.

To display the data used to compute the departure headway in Worksheet 4b, the user must use list boxes to specify the approach, lane number, and number of iteration to be displayed as shown in Figure 18. The procedure was implemented in this way to avoid the need to display 40 individual worksheets showing the computations of the departure headway for each of the four approaches, two lanes and five iterations.

As shown in Figure 18, one column was added to the right of Worksheet 4b to display the multiplication of the adjusted probability P'(i) for each combination multiplied by the saturation headway for that combination, h_{si}.

To compute the capacity of each approach in Worksheet 5, the given flow rate on the subject lane is increased by increments of 5 veh/h. For smaller increments, the computational effort increases considerably and the computed capacity varies at most by only 4 veh/h for increments of 1 veh/h. This variation was considered acceptable.

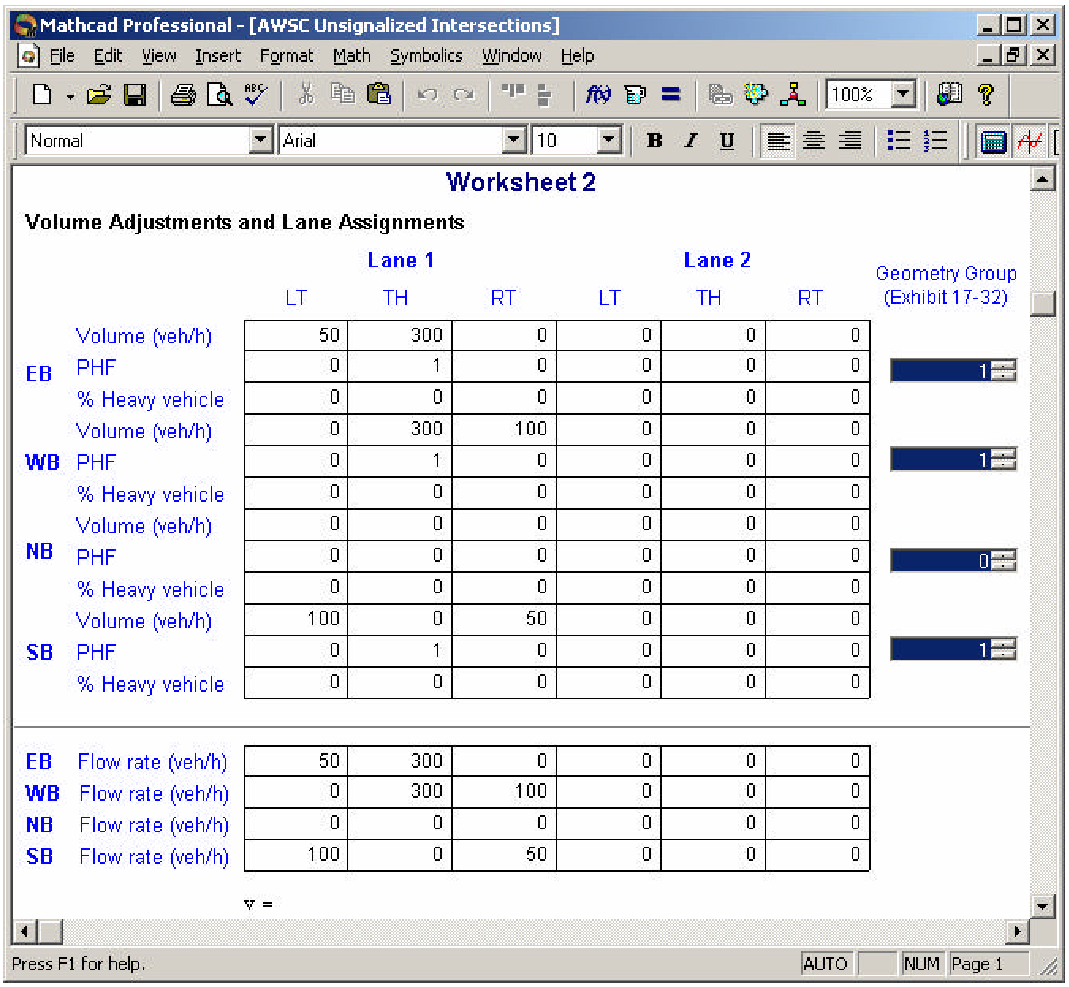
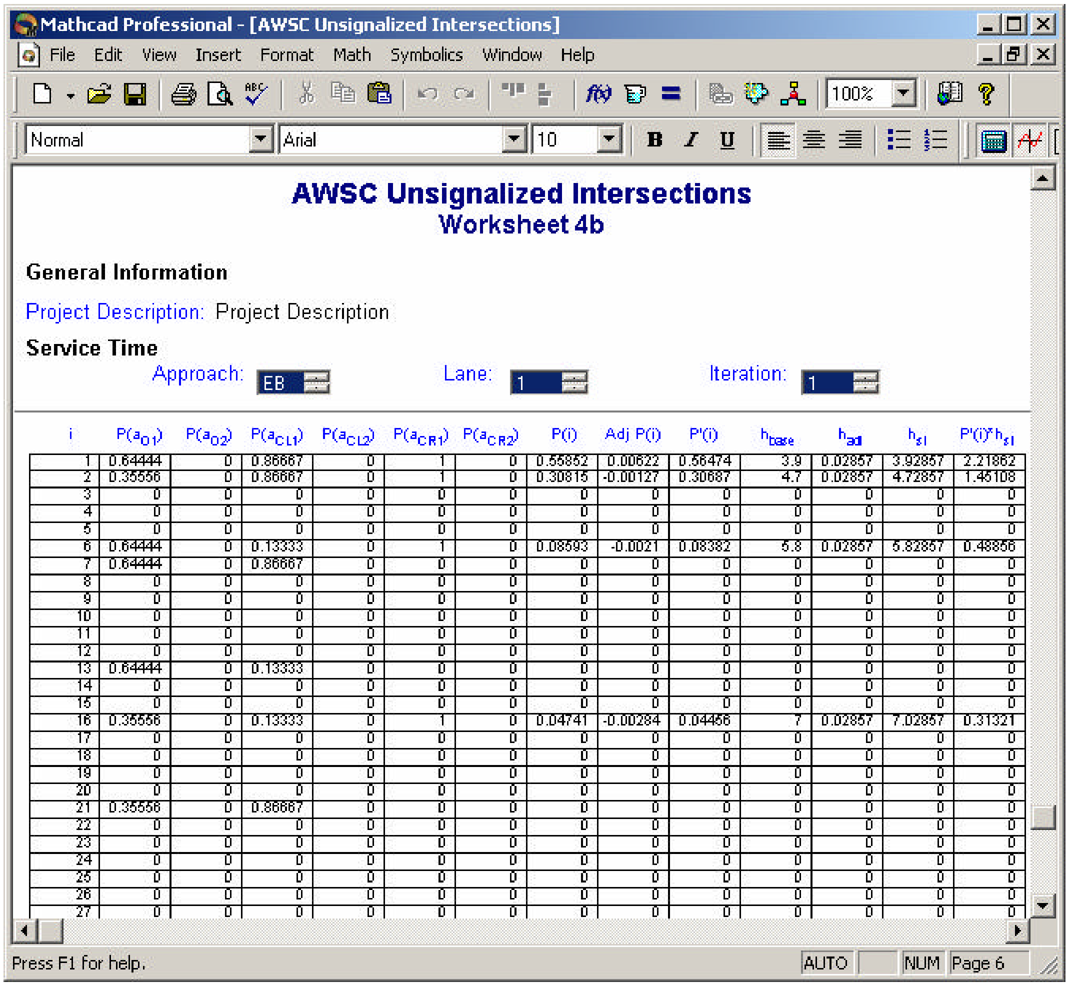


Figure 17. Worksheet 2 of AWSC – Unsignalized Intersections



i	$P(a_{O1})$	$P(a_{O2})$	$P(a_{CL1})$	$P(a_{CL2})$	$P(a_{CR1})$	$P(a_{CR2})$	$P(i)$	Adj $P(i)$	$P'(i)$	h_{base}	h_{adj}	h_{si}	$P'(i)*h_{si}$
1	0.64444	0	0.86667	0	1	0	0.55852	0.00622	0.56474	3.9	0.02857	3.92857	2.21862
2	0.35556	0	0.86667	0	1	0	0.30815	-0.00127	0.30687	4.7	0.02857	4.72857	1.45108
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0.64444	0	0.13333	0	1	0	0.08593	-0.0021	0.08382	5.8	0.02857	5.82857	0.48856
7	0.64444	0	0.86667	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0.64444	0	0.13333	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.35556	0	0.13333	0	1	0	0.04741	-0.00284	0.04456	7	0.02857	7.02857	0.31321
17	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0.35556	0	0.86667	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 18. Worksheet 4b of AWSC – Unsignalized Intersections

Roundabouts

With respect to the complexity of the procedures, this is the simplest worksheet of the five chapters that were implemented in Mathcad. The equations to compute the approach and circulating flows are displayed in the Mathcad worksheet shown in Figure 19. This is one of the few cases in the five chapters where the equations used to compute the output parameters are actually displayed in the worksheet to resemble the format of the HCM worksheet. Figure 19 also shows that the calculated flow rate is displayed separately from the input parameters.

Examples

Example 3.1, TWSC Intersection (Example Problem 1, Chapter 17 - Unsignalized Intersections, HCM (2,000))

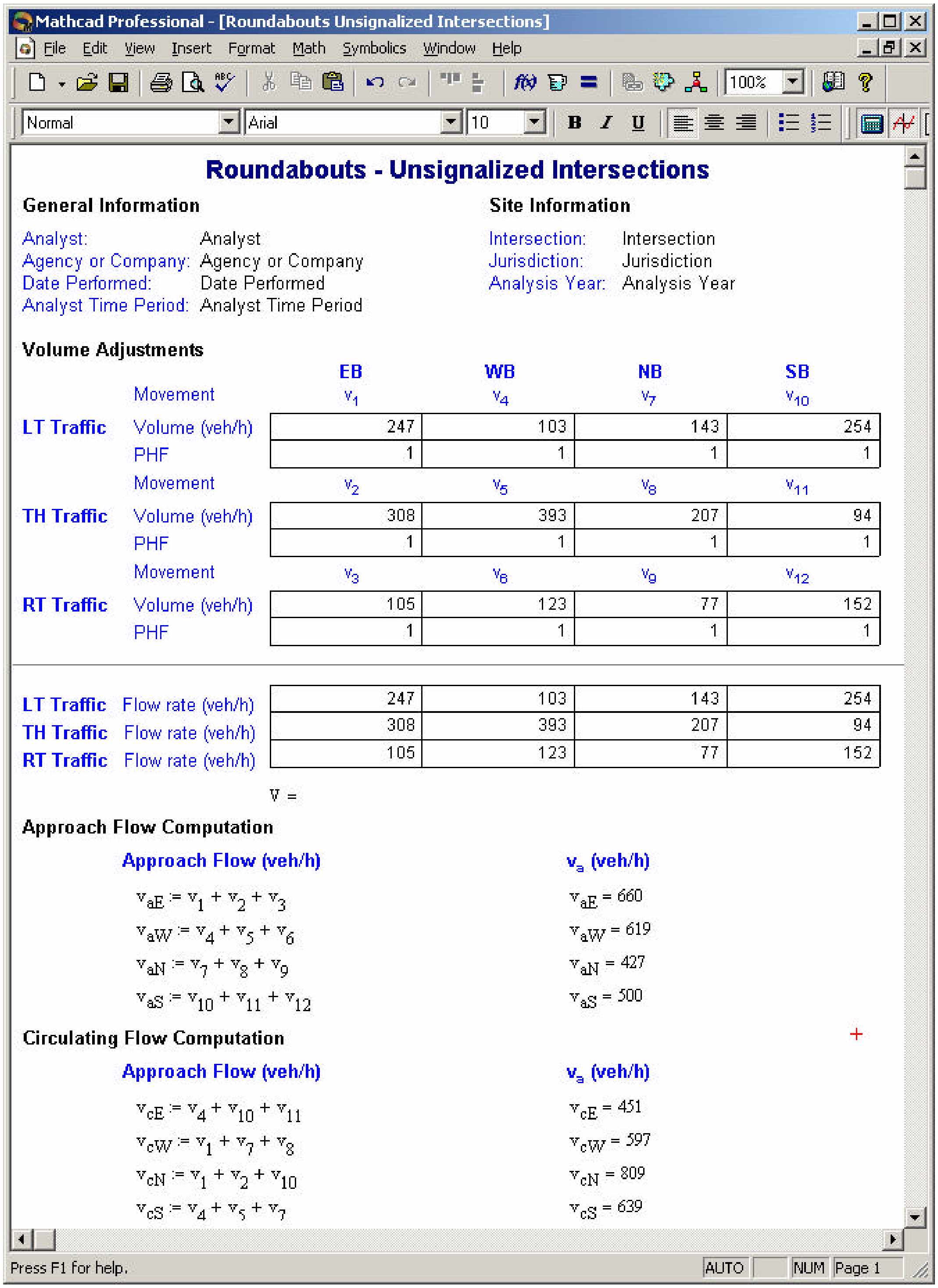
The intersection: a TWSC T-intersection with an exclusive westbound left-turn lane.

The question: what are the delay and level of service?

The facts: the facts are shown in Figures 20 and 21.

- Two-lane major street
- Two-lane minor street
- Level grade
- Stop-controlled on minor street approach
- 10 percent HV
- No special intersection geometry
- No pedestrians

Solution: the solution to the example is shown from Figure 22 to Figure 30.



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Roundabouts - Unsignalized Intersections

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analyst Time Period: Analyst Time Period

Site Information

Intersection: Intersection
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year

Volume Adjustments

		EB	WB	NB	SB
	Movement	v_1	v_4	v_7	v_{10}
LT Traffic	Volume (veh/h)	247	103	143	254
	PHF	1	1	1	1
	Movement	v_2	v_5	v_8	v_{11}
TH Traffic	Volume (veh/h)	308	393	207	94
	PHF	1	1	1	1
	Movement	v_3	v_6	v_9	v_{12}
RT Traffic	Volume (veh/h)	105	123	77	152
	PHF	1	1	1	1

LT Traffic	Flow rate (veh/h)	247	103	143	254
TH Traffic	Flow rate (veh/h)	308	393	207	94
RT Traffic	Flow rate (veh/h)	105	123	77	152

$V =$

Approach Flow Computation

Approach Flow (veh/h)	v_a (veh/h)
$v_{aE} := v_1 + v_2 + v_3$	$v_{aE} = 660$
$v_{aW} := v_4 + v_5 + v_6$	$v_{aW} = 619$
$v_{aN} := v_7 + v_8 + v_9$	$v_{aN} = 427$
$v_{aS} := v_{10} + v_{11} + v_{12}$	$v_{aS} = 500$

Circulating Flow Computation

Approach Flow (veh/h)	v_a (veh/h)
$v_{cE} := v_4 + v_{10} + v_{11}$	$v_{cE} = 451$
$v_{cW} := v_1 + v_7 + v_8$	$v_{cW} = 597$
$v_{cN} := v_1 + v_2 + v_{10}$	$v_{cN} = 809$
$v_{cS} := v_4 + v_5 + v_7$	$v_{cS} = 639$

Press F1 for help. AUTO NUM Page 1

Figure 19. Roundabouts - Unsignalized Intersections worksheet

Example 3.2, AWSC Intersection (Example Problem 4, Chapter 17 - Unsignalized Intersections, HCM (2,000))

The intersection: an AWSC T-intersection with one lane on each approach.

The question: what are the delay and level of service?

The facts: the facts are shown in Figure 31.

- Two two-lane streets
- No heavy vehicles

Solution: the solution to the example is shown from Figure 32 to Figure 34.

Example 3.3, Roundabout (Example Problem 6, Chapter 17 - Unsignalized Intersections, HCM (2,000))

Roundabout: a four-leg roundabout.

The question: what are the capacity and v/c ratio?

The facts: the facts are shown in Figure 35.

- Two two-way, two-lane streets
- One-lane roundabout
- Circulating flow less than 1,200 veh/h
- PHF = 1.00
- Duration T = 0.25 h

Solution: the solution to the example is shown in Figure 35.

The output results computed by the Mathcad worksheets compares very well with those shown in the examples of the Highway Capacity Manual. The differences between the Mathcad and manual computations are more evident in Example 3.2, where the computations involve five or more significant figures.

TWSC - Unsignalized Intersections

Worksheet 1

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analyst Time Period: Analyst Time Period

Project Description: Example

Site Information

Intersection: Intersection
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year

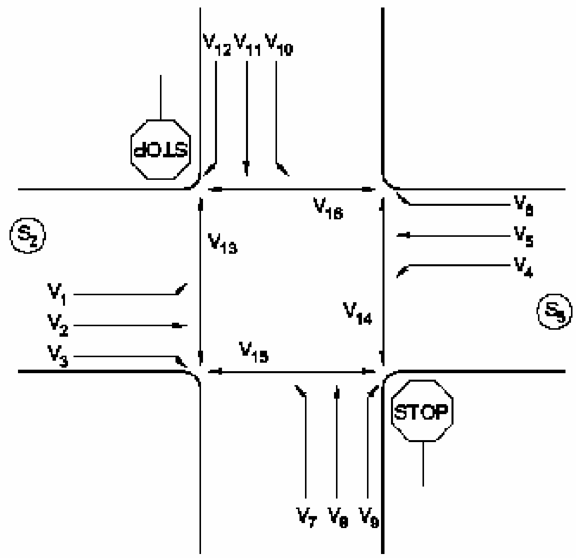
Geometrics and Movements

Number of lanes in major street (Two-way): 2

Length of study period $T := 0.25\mathrm{hr}$

Median type: Undivided

Median type affects upstreams signals



Worksheet 2

Vehicle Volumes and Adjustments

Vehicle Volumes and Adjustments

Movement	1	2	3	4	5	6	7	8	9	10	11	12
Volume (veh/h)	0	250	40	150	300	0	40	0	120	0	0	0
Peak-hour factor, PHF	0	1	1	1	1	0	1	0	1	0	0	0
Proportion of heavy vehicles, P_{HV}	0	0.1	0.1	0.1	0.1	0	0.1	0	0.1	0	0	0

P_{HV} affects follow-up time (see Worksheet 4)

Hourly flow rate (veh/h) $v_h^T =$

0	250	40	150	300	0	40	0	120	0	0	0

Pedestrian Volumes and Adjustments

Movement	13	14	15	16
Flow, V_x (ped/h)	0	0	0	0
Lane width, w (ft)	0	0	0	0
Walking speed[1], S_p (ft/s)	0	0	0	0

1. Default walking speed = 4.0 ft/s

Percent blockage, f_p (Equation 17-11) $f_p^T =$

0	0	0	0

Figure 20. Example 3.1 - Worksheet 1 and 2

TWSC Unsignalized Intersections

Worksheet 3

General Information

Project Description: PD = "Example"

Lane Designation

Movements	Lane 1			Lane 2			Lane 3			Grade, G	Right Turn[1] Channelized?
1, 2, 3	2	3	0	0	0	0	0	0	0	0	0
4, 5, 6	4	0	0	5	0	0	0	0	0	0	0
7, 8, 9	7	9	0	0	0	0	0	0	0	0	0
10, 11, 12	0	0	0	0	0	0	0	0	0	0	0

1. No (0) or Yes (1)

Flared Minor-Street Approach

Movement 9 ○ Yes ◉ No Storage space $n_9 := 0$ (number of vehicles)

Movement 12 ○ Yes ◉ No Storage space $n_{12} := 0$ (number of vehicles)

Median Storage*

* Includes raised or striped median (RM), or two-way left-turn lane (TWLTL)

Type

Movement 7 and 8 ○ Yes ◉ No Storage space $m_{78} := 0$ (number of vehicles)

Movement 10 and 11 ○ Yes ◉ No Storage space $m_{1011} := 0$ (number of vehicles)

Upstream Signals

Movements		Distance to Signal, D (ft)	Prog Speed, S_{prog} (mi/h)	Cycle Length, C (s)	Green Time g_{eff} (s)	Arrival Type	Saturation Flow Rate, s (veh/h)	Progressed Flow V_{prog} (veh/h)
S_2	protected LT	0	0	0	0	3	0	0
	TH	0	0	0	0	0	0	0
S_5	protected LT	0	0	0	0	3	0	0
	TH	0	0	0	0	0	0	0

Computing Delay to Major-Street Vehicles

Data for Computing Effect of Delay to Major-Street Vehicles	S_2 Approach	S_5 Approach
Shared-lane volume, major-street through vehicles, v_{i1} blocked by LT	0	0
Shared-lane volume, major-street right-turn vehicles, v_{i2} blocked by LT	0	0
Saturation flow rate, major-street through vehicles, s_{i1}	0	0
Saturation flow rate, major-street right-turn vehicles, s_{i2}	0	0
Number of major-street through lanes	0	0
Length of study period, T (h)	0	0

Figure 21. Example 3.1 - Worksheet 3

TWSC Unsignalized Intersections

Worksheet 4

General Information

Project Description: PD = "Example"

Critical Gap and Follow-Up Time

Movement		Major LT 1	4	Minor RT 9	12	Minor TH 8	11	Minor LT 7	10
$t_{c,base}$ (Exhibit 17-5)		0	4.1	6.2	0	0	0	7.1	0
$t_{c,HV}$		0	1	1	0	0	0	1	0
P_{HV} (from Worksheet 2)		0	0.1	0.1	0	0	0	0.1	0
$t_{c,G}$		0	0	0.1	0	0	0	0.2	0
G (from Worksheet 3)		0	0	0	0	0	0	0	0
$t_{3,LT}$		0	0	0	0	0	0	0.7	0
$t_{c,T}$	single stage	0	0	0	0	0	0	0	0
	two stage	0	0	0	0	0	0	0	0
$t_{c,x}$ (Eq. 17-1)	single stage	0	4.2	6.3	0	0	0	6.5	0
	first stage	0	0	0	0	0	0	0	0
	second stage	0	0	0	0	0	0	0	0

$Results_{tc}$ =

Movement	Major LT 1	4	Minor RT 9	12	Minor TH 8	11	Minor LT 7	10
$t_{f,base}$ (Exhibit 17-5)	0	2.2	3.3	0	0	0	3.5	0
t_{fHV}	0	0.9	0.9	0	0	0	0.9	0
P_{HV} (from Worksheet 2)	0	0.1	0.1	0	0	0	0.1	0
t_f (Equation 17-2)	0	2.29	3.39	0	0	0	3.59	0

$Results_{tf}$ =

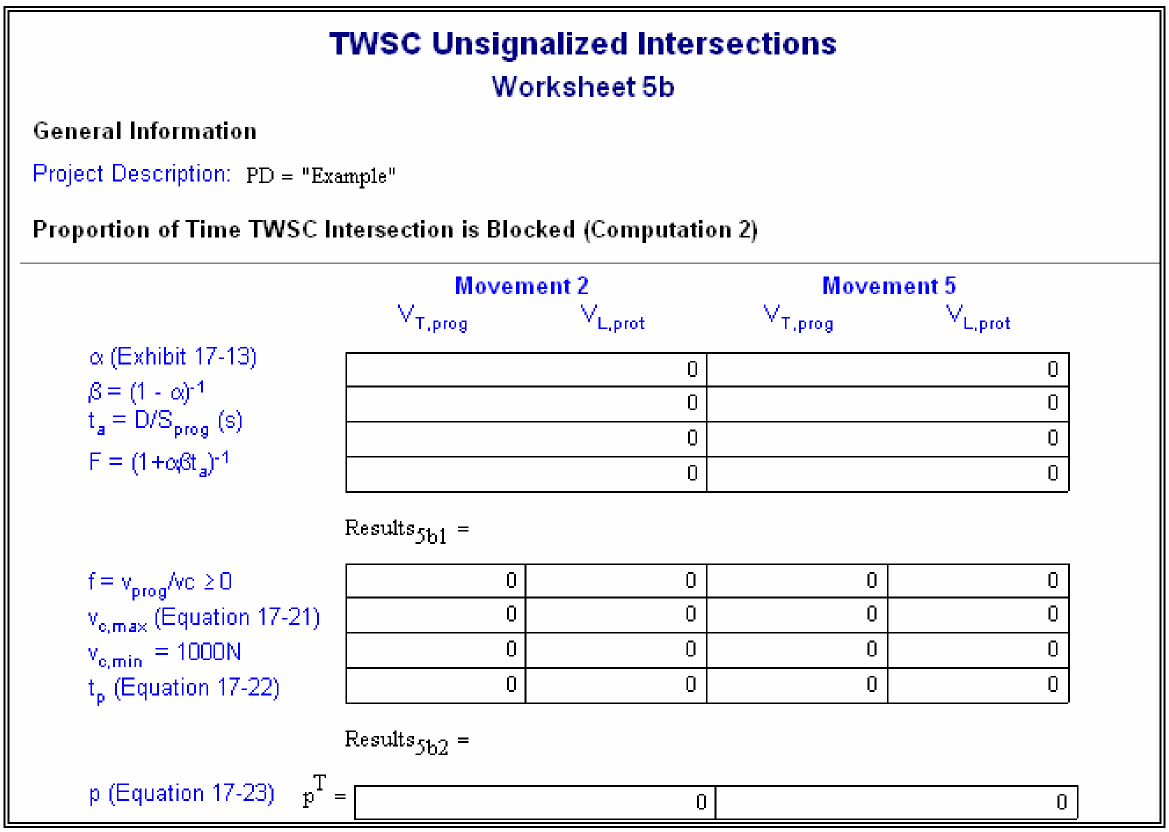
Worksheet 5a

Time to Clear Standing Queue (Computation 1)

	Movement 2 $V_{T,prog}$	Movement 2 $V_{L,prot}$	Movement 5 $V_{T,prog}$	Movement 5 $V_{L,prot}$
Effective green, g_{eff} (s)	0	0	0	0
Cycle length, C (s)	0	0	0	0
Saturation flow rate, s (veh/h)	0	0	0	0
Arrival type	0	3	0	3
Progressed flow, v_{prog} (veh/h)	0	0	0	0
R_p (from Chapter 16)	0	1	0	1
Prop. of veh. arriving on green, P	0	0	0	0
g_{q1} (Equation 17-18)	0	0	0	0
g_{q2} (Equation 17-19)	0	0	0	0
g_q (Equation 17-20)	0	0	0	0

$Results_{5a}$ =

Figure 22. Example 3.1 - Worksheet 4 and 5a



TWSC Unsignalized Intersections

Worksheet 5b

General Information

Project Description: PD = "Example"

Proportion of Time TWSC Intersection is Blocked (Computation 2)

	Movement 2	Movement 5
α (Exhibit 17-13)	0	0
$\beta = (1 - \alpha)^{-1}$	0	0
$t_a = D/S_{prog}$ (s)	0	0
$F = (1+\alpha\beta t_a)^{-1}$	0	0

$Results_{5b1}$ =

	Movement 2 $V_{T,prog}$	Movement 2 $V_{L,prot}$	Movement 5 $V_{T,prog}$	Movement 5 $V_{L,prot}$
$f = v_{prog}/vc \geq 0$	0	0	0	0
$v_{c,max}$ (Equation 17-21)	0	0	0	0
$v_{c,min}$ = 1000N	0	0	0	0
t_p (Equation 17-22)	0	0	0	0

$Results_{5b2}$ =

p (Equation 17-23) p^T =	0	0

Figure 23. Example 3.1 - Worksheet 5b

Worksheet 5c

Platoon Event Periods (Computation 3)

p_2 (from Worksheet 5b)	0
p_5 (from Worksheet 5b)	0
p_{dom} (Equation 17-24)	0
p_{subo} (Equation 17-25)	0
Constrained or unconstrained (Equation 17-26, 17-27)	"Unconstrained"

Results5c1 =

Proportion for Minor Movements, p_x

	Single-Stage (Exhibit 17-16)	**Two-Stage** **Stage I**	**Stage II**
p_1	1	0	0
p_4	1	0	0
p_7	1	0	0
p_8	1	0	0
p_9	1	0	0
p_{10}	1	0	0
p_{11}	1	0	0
p_{12}	1	0	0

Results5c2 =

Table that allows the user modify some or all values of p_x.
A value of 0 in this table won't modify the value computed by the worksheet.

Proportion for Minor Movements, p_x

	Single-Stage	**Two-Stage** **Stage I**	**Stage II**
p_1	0	0	0
p_4	0	0	0
p_7	0	0	0
p_8	0	0	0
p_9	0	0	0
p_{10}	0	0	0
p_{11}	0	0	0
p_{12}	0	0	0

Figure 24. Example 3.1 - Worksheet 5c

TWSC Unsignalized Intersections
Worksheet 5d

General Information

Project Description: PD = "Example"

Conflicting Flows During Unblocked Period (Computation 4)

Single-Stage

Movements	1	4	7	8	9	10	11	12
$v_{c,x}$ (Exhibit 17-4)	300	290	870	870	270	930	890	300
s (veh/h)	1700	1700	1700	1700	1700	1700	1700	1700
p_x (from Worksheet 5c)	1	1	1	1	1	1	1	1
$v_{c,u,x}$ (Equation 17-28)	300	290	870	870	270	930	890	300

Results_{5d1} =

Two-Stage

Movements	7		8		10		11	
	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II
$v_{c,x}$ (Exhibit 17-4)	0	0	0	0	0	0	0	0
s (veh/h)	0	0	0	0	0	0	0	0
p_x (from Worksheet 5c)	0	0	0	0	0	0	0	0
$v_{c,u,x}$ (Equation 17-28)	0	0	0	0	0	0	0	0

Results_{5d2} =

Worksheet 5e

Capacity During Unblocked Period (Computation 5)

Single-Stage

Movements	1	4	7	8	9	10	11	12
p_x (from Worksheet 5c)	1	1	1	1	1	1	1	1
$c_{r,x}$ (Equation 17-3)	0	1227	312	0	750	0	0	0
$c_{plat,x}$ (Equation 17-29)	0	1227	312	0	750	0	0	0

Results_{5e1} =

Two-Stage

Movements	7		8		10		11	
	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II
p_x (from Worksheet 5c)	0	0	0	0	0	0	0	0
$c_{r,x}$ (Equation 17-3)	0	0	0	0	0	0	0	0
$c_{plat,x}$ (Equation 17-29)	0	0	0	0	0	0	0	0

Results_{5e2} =

Figure 25. Example 3.1 - Worksheet 5d and 5e

TWSC Unsignalized Intersections
Worksheet 6

General Information

Project Description: PD = "Example"

Impedance and Capacity Calculation

Step 1: RT from Minor Street	v_9	v_{12}
Conflicting flows (Exhibit 17-4)	$V_{c9} = 270$	$V_{c12} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p9} = 750$	$c_{p12} = 0$
Ped impedance factor (Equation 17-12)	$p_{p9} = 1$	$p_{p12} = 0$
Movement capacity (Equation 17-4)	$c_{m9} = 750$	$c_{m12} = 0$
Prob of queue-free state (Equation 17-5)	$p_{09} = 0.84$	$p_{012} = 1$
Step 2: LT from Major Street	v_4	v_1
Conflicting flows (Exhibit 17-4)	$V_{c4} = 290$	$V_{c1} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p4} = 1227$	$c_{p1} = 0$
Ped impedance factor (Equation 17-12)	$p_{p4} = 1$	$p_{p1} = 0$
Movement capacity (Equation 17-4)	$c_{m4} = 1227$	$c_{m1} = 0$
Prob of queue-free state (Equation 17-5)	$p_{04} = 0.878$	$p_{01} = 1$
Major left shared lane prob of queue-free state (Equation 17-16)	$pp_{04} = 0$	$pp_{01} = 1$
Step 3: TH from Minor Street (4-leg intersections only)	v_8	v_{11}
Conflicting flows (Exhibit 17-4)	$V_{c8} = 0$	$V_{c11} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p8} = 0$	$c_{p11} = 0$
Ped impedance factor (Equation 17-12)	$p_{p8} = 0$	$p_{p11} = 0$
Capacity adjustment factor due to impeding mov. (Equation 17-13)	$f_8 = 0$	$f_{11} = 0$
Movement capacity (Equation 17-7)	$c_{m8} = 0$	$c_{m11} = 0$
Prob of queue-free state (Equation 17-5)	$p_{08} = 0$	$p_{011} = 0$
Step 4: LT from Minor Street (4-leg intersections only)	v_7	v_{10}
Conflicting flows (Exhibit 17-4)	$v_{c74} = 0$	$v_{c104} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p7} = 0$	$c_{p10} = 0$
Ped impedance factor (Equation 17-12)	$p_{p7} = 0$	$p_{p10} = 0$
Major left, minor through impedance factor	$p''_7 = 0$	$p''_{10} = 0$
Major left, minor through adjusted impedance factor (Equation 17-8)	$p'_7 = 0$	$p'_{10} = 0$
Capacity adjustment factor due to impeding mov. (Equation 17-14)	$f_7 = 0$	$f_{10} = 0$
Movement capacity (Equation 17-10)	$c_{m74} = 0$	$c_{m104} = 0$
Step 5: LT from Minor Street (T-intersections only)	v_7	v_{10}
Conflicting flows (Exhibit 17-4)	$v_{c75} = 870$	$v_{c105} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p75} = 312$	$c_{p105} = 0$
Ped impedance factor (Equation 17-12)	$p_{p75} = 1$	$p_{p105} = 0$
Capacity adjustment factor due to impeding mov. (Equation 17-13)	$f_{75} = 0.878$	$f_{105} = 0$
Movement capacity (Equation 17-7)	$c_{m75} = 274$	$c_{m105} = 0$

Figure 26. Example 3.1 - Worksheet 6

TWSC Unsignalized Intersections

Worksheet 7a

General Information

Project Description: PD = "Example"

Effect of Two-Stage Gap Acceptance

Step 3: TH from Minor Street	v_8	v_{11}
Part I - First Stage		
Conflicting flows (Exhibit 17-4)	$v_{cI8} = 0$	$v_{cI11} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{pI8} = 0$	$c_{pI11} = 0$
Ped impedance factor (Equation 17-12)	$p_{pI8} = 0$	$p_{pI11} = 0$
Capacity adjustment factor due to impeding movement (Equation 17-6 or 17-13)	$f_{I8} = 0$	$f_{I11} = 0$
Movement capacity (Equation 17-7)	$c_{mI8} = 0$	$c_{mI11} = 0$
Prob of queue-free state (Equation 17-5)	$p_{0I8} = 0$	$p_{0I11} = 0$
Part II - Second Stage		
Conflicting flows (Exhibit 17-4)	$v_{cII8} = 0$	$v_{cII11} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{pII8} = 0$	$c_{pII11} = 0$
Ped impedance factor (Equation 17-12)	$p_{pII8} = 0$	$p_{pII11} = 0$
Capacity adjustment factor due to impeding movement (Equation 17-6 or 17-13)	$f_{II8} = 0$	$f_{II11} = 0$
Movement capacity (Equation 17-7)	$c_{mII8} = 0$	$c_{mII11} = 0$
Prob of queue-free state (Equation 17-5)	$p_{0II8} = 0$	$p_{0II11} = 0$
Part III - Single Stage		
Conflicting flows (Exhibit 17-4)	$V_{c8} = 0$	$V_{c11} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p8} = 0$	$c_{p11} = 0$
Ped impedance factor (Equation 17-12)	$p_{p8} = 0$	$p_{p11} = 0$
Capacity adjustment factor due to impeding movement (Equation 17-6 or 17-13)	$f_8 = 0$	$f_{11} = 0$
Movement capacity (Equation 17-7)	$c_{m8} = 0$	$c_{m11} = 0$
Result for Two-Stage Process		
a (Exhibit 17-30)	$a_8 = 0$	$a_{11} = 0$
y (Equation 17-31)	$y_8 = 0$	$y_{11} = 0$
c_T (Equation 17-32 or 17-33)	$c_{T8} = 0$	$c_{T11} = 0$
Prob of queue-free state (Equation 17-5)	$p_{08} = 0$	$p_{011} = 0$

Figure 27. Example 3.1 - Worksheet 7a

TWSC Unsignalized Intersections

Worksheet 7b

General Information

Project Description: PD = "Example"

Effect of Two-Stage Gap Acceptance

Step 4: LT from Minor Street	v_7	v_{10}
Part I - First Stage		
Conflicting flows (Exhibit 17-4)	$v_{cI7} = 0$	$v_{cI10} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{pI7} = 0$	$c_{pI10} = 0$
Ped impedance factor (Equation 17-12)	$p_{pI7} = 0$	$p_{pI10} = 0$
Capacity adjustment factor due to impeding movements	$f_{I7} = 0$	$f_{I10} = 0$
Movement capacity (Equation 17-7)	$c_{mI7} = 0$	$c_{mI10} = 0$
Part II - Second Stage		
Conflicting flows (Exhibit 17-4)	$v_{cII7} = 0$	$v_{cII10} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{pII7} = 0$	$c_{pII10} = 0$
Ped impedance factor (Equation 17-12)	$p_{pII7} = 0$	$p_{pII10} = 0$
Capacity adjustment factor due to impeding movements	$f_{II7} = 0$	$f_{II10} = 0$
Movement capacity (Equation 17-7)	$c_{mII7} = 0$	$c_{mII10} = 0$
Part III - Single Stage		
Conflicting flows (Exhibit 17-4)	$V_{c7} = 0$	$V_{c10} = 0$
Potential capacity (Equation 17-3 or 17-29)	$c_{p7} = 0$	$c_{p10} = 0$
Ped impedance factor (Equation 17-12)	$p_{p7} = 0$	$p_{p10} = 0$
Major left, minor through impedance factor	$p''_7 = 0$	$p''_{10} = 0$
Major left, minor through adjusted impedance factor (Equation 17-8)	$p'_7 = 0$	$p'_{10} = 0$
Capacity adjustment factor due to impeding movements (Equation 17-9 or 17-14)	$f_7 = 0$	$f_{10} = 0$
Movement capacity (Equation 17-7)	$c_{m7} = 0$	$c_{m10} = 0$
Result for Two-Stage Process		
a (Exhibit 17-30)	$a_7 = 0$	$a_{10} = 0$
y (Equation 17-31)	$y_7 = 0$	$y_{10} = 0$
c_T (Equation 17-32 or 17-33)	$c_{T7} = 0$	$c_{T10} = 0$

Figure 28. Example 3.1 - Worksheet 7b

TWSC Unsignalized Intersections

Worksheet 8

General Information

Project Description: PD = "Example"

Shared-Lane Capacity

Lane	v (veh/h) Movement 7	v (veh/h) Movement 8	v (veh/h) Movement 9	c_m (veh/h) Movement 7	c_m (veh/h) Movement 8	c_m (veh/h) Movement 9	c_{SH} (veh/H)
1	40	0	120	274	0	750	523
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0

SLC_1 =

Lane	Movement 10	Movement 11	Movement 12	Movement 10	Movement 11	Movement 12	
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0

SLC_2 =

Worksheet 9

Effect of Flared Minor-Street Approaches

Lane1 = 0 Lane2 = 0

	Movement 7	Movement 8	Movement 9	Movement 10	Movement 11	Movement 12
c_{sep} (from Worksheet 6 or 7)	0	0	0	0	0	0
volume (from Worksheet 2)	0	0	0	0	0	0
delay (Equation 17-38)	0	0	0	0	0	0
Q_{sep} (Equation 17-34)	0	0	0	0	0	0
Q_{sep} + 1	0	0	0	0	0	0
round(Q_{sep} + 1)	0	0	0	0	0	0

$Results_{9a}$ =

n_{max} (Equation 17-35)	0	0
c_{SH}	0	0
c_{sep}	0	0
n	0	0
c_{act} (Equation 17-36)	0	0

$Results_{9b}$ =

Figure 29. Example 3.1 - Worksheet 8 and 9

TWSC Unsignalized Intersections

Worksheet 10

General Information

Project Description: PD = "Example"

Control Delay, Queue Length, Level of Service

Lane	Movements	v (veh/h)	c_m (veh/h)	v/c	Queue Length (Eq. 17-37)	Control Delay (Eq. 17-38)	LOS (Exhibit 17-2)	Delay and LOS
1	"7 9"	160	523	0.306	"< 2"	14.9	"B"	14.9
2	0	0	0	0	0	0	0	"B"
3	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0

$Results_{101}$ =

Movement	v (veh/h)	c_m (veh/h)	v/c	Queue Length (Equation 17-37)	Control Delay (Equation 17-38)	LOS (Exhibit 17-2)
1	0	0	0	0	0	0
4	150	1227	0.122	"< 1"	8.3	"A"

$Results_{102}$ =

Worksheet 11

Delay to Rank 1 Vehicles

	S_2 Approach	S_5 Approach
$p_{0,j}$ (Equation 17-5)	0	0
v_{i1}, volume for Stream 2 or 5	0	0
v_{i2}, volume for Stream 3 or 6	0	0
s_{i1}, saturation flow rate for Stream 2 or 5	0	0
s_{i2}, saturation flow rate for Stream 3 or 6	0	0
$p^*_{0,j}$ (Equation 17-5)	0	0
$d_{major\ left}$, delay for Stream 1 or 4	0	0
N, number of major-street through lanes	0	0
$d_{Rank\ 1}$, delay for Stream 2 or 5 (Equation 17-39)	0	0

$Results_{11}$ =

Figure 30. Example 3.1 - Worksheet 10

AWSC - Unsignalized Intersections

Worksheet 1

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analyst Time Period: Analyst Time Period

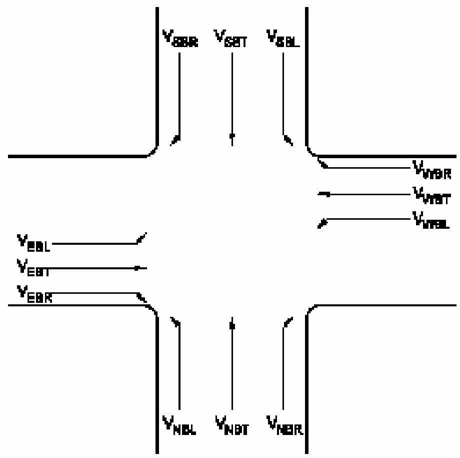
Site Information

Intersection: Intersection
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year

Project Description: Examples

Geometrics and Movements

Length of study period $T := 0.25\text{hr}$



Worksheet 2

Volume Adjustments and Lane Assignments

		Lane 1 LT	Lane 1 TH	Lane 1 RT	Lane 2 LT	Lane 2 TH	Lane 2 RT	Geometry Group (Exhibit 17-32)
EB	Volume (veh/h)	50	300	0	0	0	0	
	PHF	0	1	0	0	0	0	1
	% Heavy vehicle	0	0	0	0	0	0	
WB	Volume (veh/h)	0	300	100	0	0	0	
	PHF	0	1	0	0	0	0	1
	% Heavy vehicle	0	0	0	0	0	0	
NB	Volume (veh/h)	0	0	0	0	0	0	
	PHF	0	0	0	0	0	0	0
	% Heavy vehicle	0	0	0	0	0	0	
SB	Volume (veh/h)	100	0	50	0	0	0	
	PHF	0	1	0	0	0	0	1
	% Heavy vehicle	0	0	0	0	0	0	

EB	Flow rate (veh/h)	50	300	0	0	0	0
WB	Flow rate (veh/h)	0	300	100	0	0	0
NB	Flow rate (veh/h)	0	0	0	0	0	0
SB	Flow rate (veh/h)	100	0	50	0	0	0

v =

Figure 31. Example 3.2 - Worksheet 1 and 2

AWSC Unsignalized Intersections

Worksheet 3

General Information

Project Description: PD = "Examples"

Saturation Headways

	EB L1	EB L2	WB L1	WB L2	NB L1	NB L2	SB L1	SB L2
Total lane flow rate	350	0	400	0	0	0	150	0
Left-turn flow rate in lane	50	0	0	0	0	0	100	0
Right-turn flow rate in lane	0	0	100	0	0	0	50	0
Proportion LT in lane	0.143	0	0	0	0	0	0.667	0
Proportion RT in lane	0	0	0.25	0	0	0	0.333	0
Proportion HV in lane	0	0	0	0	0	0	0	0
$h_{LT\text{-}adj}$ (Exhibit 17-33)	0.2	0	0.2	0	0	0	0.2	0
$h_{RT\text{-}adj}$ (Exhibit 17-33)	-0.6	0	-0.6	0	0	0	-0.6	0
$h_{HV\text{-}adj}$ (Exhibit 17-33)	1.7	0	1.7	0	0	0	1.7	0
h_{adj} (Equation 17-56)	0.029	0	-0.15	0	0	0	-0.067	0

$Results_3$ =

Worksheet 4a

Departure Headway

	EB L1	EB L2	WB L1	WB L2	NB L1	NB L2	SB L1	SB L2
Total lane flow rate	350	0	400	0	0	0	150	0
h_d, initial value (s)	3.2	0	3.2	0	0	0	3.2	0
x, initial value (Eq. 17-57)	0.311	0	0.356	0	0	0	0.133	0
h_d, Iteration 1	4.471	0	4.256	0	0	0	4.953	0
h_d, difference	1.271	0	1.056	0	0	0	1.753	0
h_d, Iteration 2	4.715	0	4.504	0	0	0	5.316	0
h_d, difference	0.243	0	0.248	0	0	0	0.363	0
h_d, Iteration 3	4.769	0	4.554	0	0	0	5.391	0
h_d, difference	0.054	0	0.05	0	0	0	0.074	0
h_d, Iteration 4	0	0	0	0	0	0	0	0
h_d, difference	0	0	0	0	0	0	0	0
h_d, Iteration 5	0	0	0	0	0	0	0	0
h_d, difference	0	0	0	0	0	0	0	0
Convergence?	"Y"	0	"Y"	0	0	0	"Y"	0
h_d, final	4.769	0	4.554	0	0	0	5.391	0
x, final	0.464	0	0.506	0	0	0	0.225	0

$Results_{4a}$ =

Figure 32. Example 3.2 - Worksheet 3 and 4a

AWSC Unsignalized Intersections
Worksheet 4b

General Information

Project Description: PD = "Examples"

Service Time

Approach: EB Lane: 1 Iteration: 1

i	$P(a_{O1})$	$P(a_{O2})$	$P(a_{CL1})$	$P(a_{CL2})$	$P(a_{CR1})$	$P(a_{CR2})$	P(i)	Adj P(i)	P'(i)	h_{base}	h_{adj}	h_{si}	$P'(i)*h_{si}$
1	0.64444	0	0.86667	0	1	0	0.55852	0.00622	0.56474	3.9	0.02857	3.92857	2.21862
2	0.35556	0	0.86667	0	1	0	0.30815	-0.00127	0.30687	4.7	0.02857	4.72857	1.45108
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0.64444	0	0.13333	0	1	0	0.08593	-0.0021	0.08382	5.8	0.02857	5.82857	0.48856
7	0.64444	0	0.86667	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0.64444	0	0.13333	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.35556	0	0.13333	0	1	0	0.04741	-0.00284	0.04456	7	0.02857	7.02857	0.31321
17	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0.35556	0	0.86667	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0	0	0
64	0.35556	0	0.13333	0	0	0	0	0	0	0	0	0	0

$Results_{4b}$ =

Figure 33. Example 3.2 - Worksheet 4b

AWSC Unsignalized Intersections

Worksheet 5

General Information

Project Description: PD = "Examples"

Capacity and Level of Service

	EB L1	EB L2	WB L1	WB L2	NB L1	NB L2	SB L1	SB L2
Total lane flow rate	350	0	400	0	0	0	150	0
Departure headway, h_d (s)	4.769	0	4.554	0	0	0	5.391	0
Degree of utilization, x	0.464	0	0.506	0	0	0	0.225	0
Move-up time, m (s)	2	0	2	0	0	0	2	0
Service time, t_s (s)	2.769	0	2.554	0	0	0	3.391	0
Capacity (veh/h)	735	0	770	0	0	0	610	0
Delay (s) (Equation 17-55)	11.8	0	12.1	0	0	0	9.9	0
Level of service (Ex. 17-22)	"B"	0	"B"	0	0	0	"A"	0

$Results_{5a}$ =

	EB	WB	NB	SB
Delay, approach (s/veh)	11.8	12.1	0	9.9
Level of service, approach	"B"	"B"	0	"A"

$Results_{5b}$ =

Delay, intersection (s/veh) $d_I = 11.3$

Level of service, intersection Los_I = "B"

Figure 34. Example 3.2 - Worksheet 5

Roundabouts - Unsignalized Intersections

General Information

Analyst:	Analyst
Agency or Company:	Agency or Company
Date Performed:	Date Performed
Analyst Time Period:	Analyst Time Period

Site Information

Intersection:	Intersection
Jurisdiction:	Jurisdiction
Analysis Year:	Analysis Year

Volume Adjustments

		EB	WB	NB	SB
	Movement	v_1	v_4	v_7	v_{10}
LT Traffic	Volume (veh/h)	247	103	143	254
	PHF	1	1	1	1
	Movement	v_2	v_5	v_8	v_{11}
TH Traffic	Volume (veh/h)	308	393	207	94
	PHF	1	1	1	1
	Movement	v_3	v_6	v_9	v_{12}
RT Traffic	Volume (veh/h)	105	123	77	152
	PHF	1	1	1	1

LT Traffic	Flow rate (veh/h)	247	103	143	254
TH Traffic	Flow rate (veh/h)	308	393	207	94
RT Traffic	Flow rate (veh/h)	105	123	77	152

V =

Approach Flow Computation

Approach Flow (veh/h)	v_a (veh/h)
$v_{aE} := v_1 + v_2 + v_3$	$v_{aE} = 660$
$v_{aW} := v_4 + v_5 + v_6$	$v_{aW} = 619$
$v_{aN} := v_7 + v_8 + v_9$	$v_{aN} = 427$
$v_{aS} := v_{10} + v_{11} + v_{12}$	$v_{aS} = 500$

Circulating Flow Computation

Approach Flow (veh/h)	v_a (veh/h)
$v_{cE} := v_4 + v_{10} + v_{11}$	$v_{cE} = 451$
$v_{cW} := v_1 + v_7 + v_8$	$v_{cW} = 597$
$v_{cN} := v_1 + v_2 + v_{10}$	$v_{cN} = 809$
$v_{cS} := v_4 + v_5 + v_7$	$v_{cS} = 639$

Capacity Computation		EB	WB	NB	SB
Capacity (Eq. 17-70)	Upper bound	971	864	728	835
	Lower bound	788	693	573	667
v/c Ratio	Upper bound	0.68	0.716	0.587	0.599
	Lower bound	0.838	0.893	0.745	0.75

Results =

Figure 35. Example 3.3 - Roundabouts

CHAPTER 4

BASIC FREEWAY SEGMENTS

As mentioned previously, units were implemented in the methodology of this chapter. Existing units in Mathcad such as mile (mi) and hour (hr) were used, and new units were defined as needed.

In the Site Information section on the upper part of the worksheet, radio buttons are used to select rural or urban Freeway Segment Area as shown in Figure 36. In the Flow Inputs section, list boxes are used to define the type of General Terrain (level, rolling or mountainous) and the Grade (upgrade or downgrade). If the General Terrain option is used, "None" must be selected in the Grade list box. Similarly, "None" must be selected for the General Terrain list box if a grade and a length for that grade are specified.

Although the Driver Type is selected from Commuter/Weekday or Recreational/Weekend as shown in Figure 36, the user must specify the driver population factor, f_p, because values of f_p range from 0.85 to 1.00 for each type of driver.

The exhibits for the Passenger-car equivalents for trucks and buses, E_T, and Passenger-car equivalents for RVs, E_R, on upgrades and downgrades were implemented in matrices where each matrix contains the data for a range of grades. This facilitates the selection of the parameters depending on the specified grade. Figure 37 shows the procedure to select E_R for RVs. The exhibits for speed adjustment factors in the HCM were implemented in the Mathcad worksheets with their own units. An example of these factors is shown in Figure 38.

The graph of the speed-flow curves and the actual performance of the freeway segment is located at the end of the worksheet due to the calculation flow used by Mathcad.

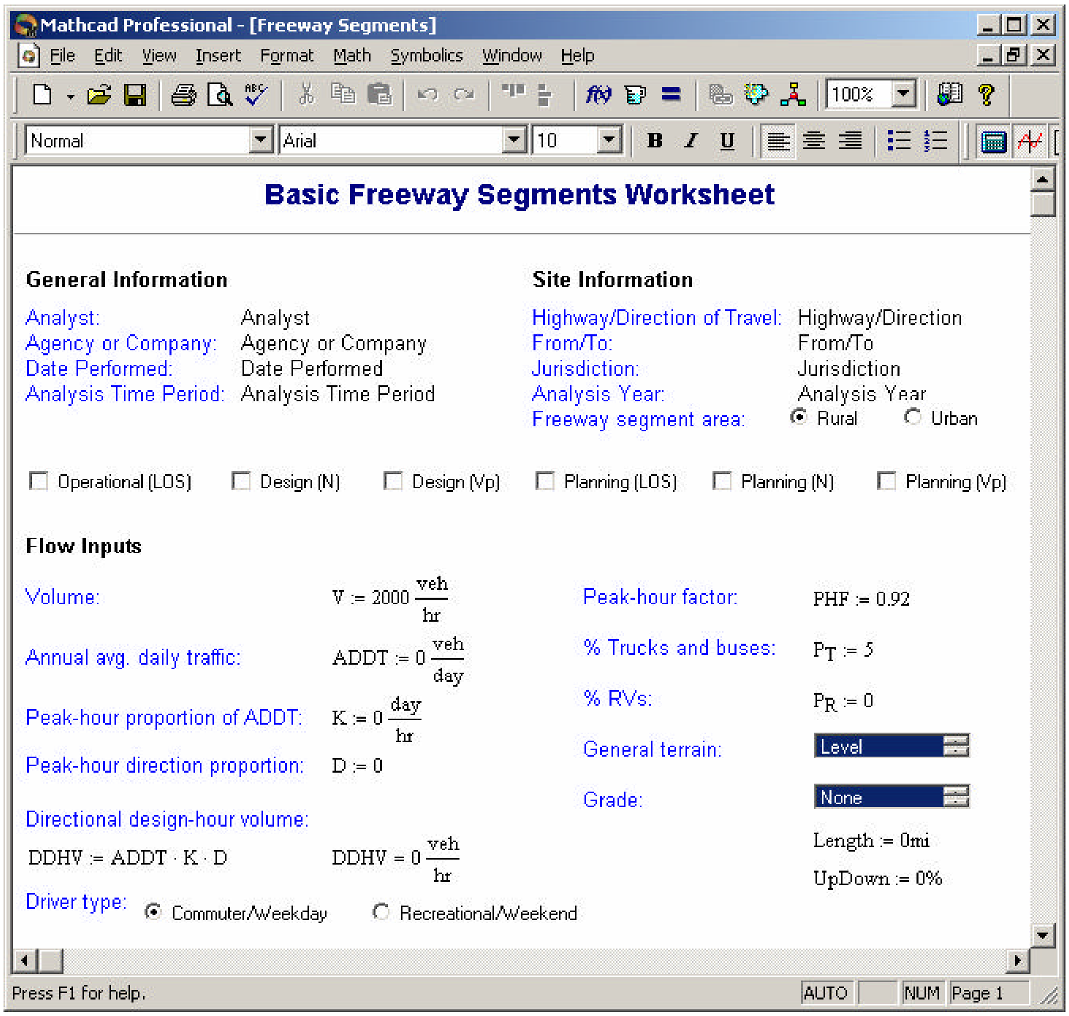


Figure 36. Upper part of the Basic Freeway Segment worksheet

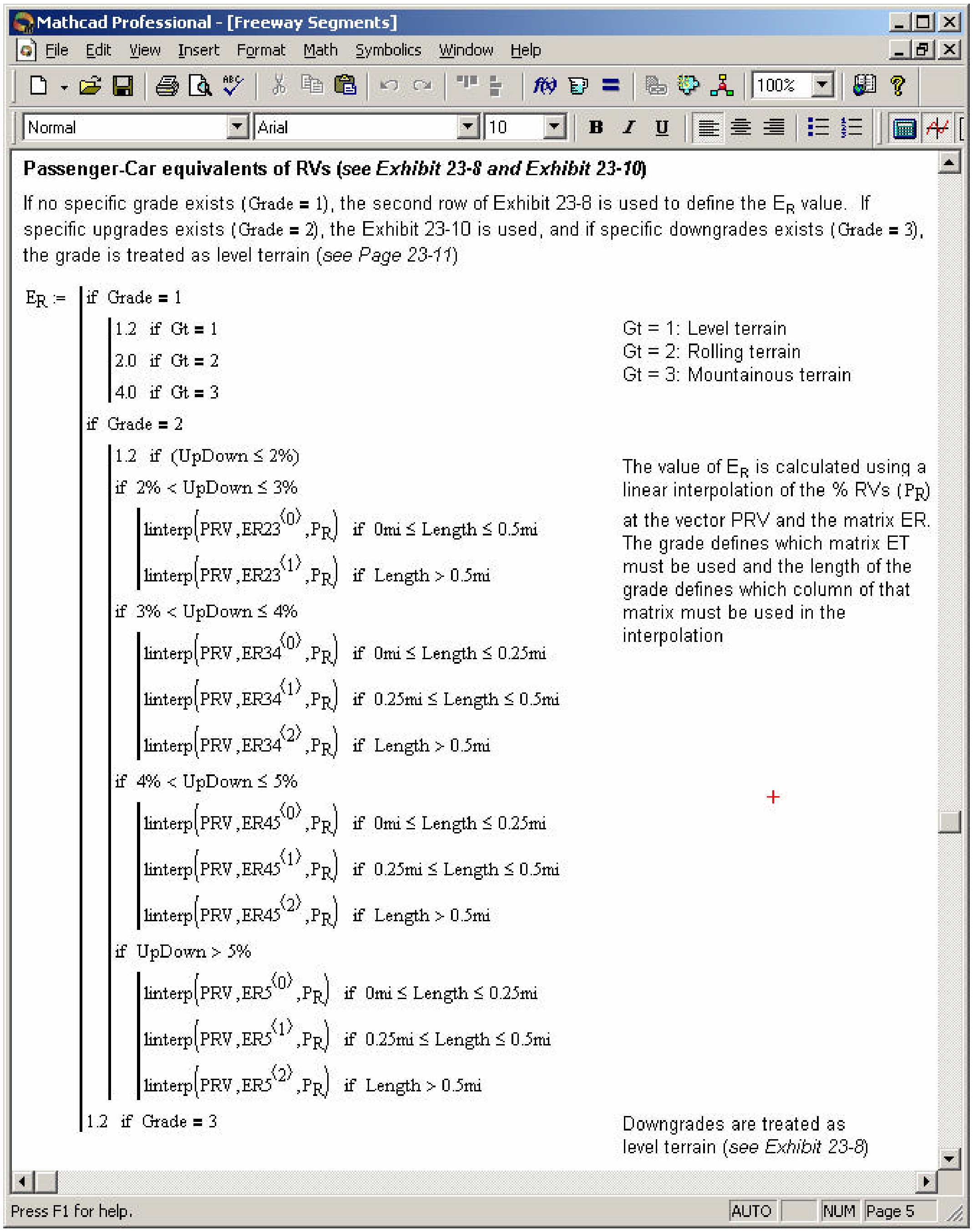


Figure 37. Procedure to select ER for RVs in the Basic Freeway Segment worksheet

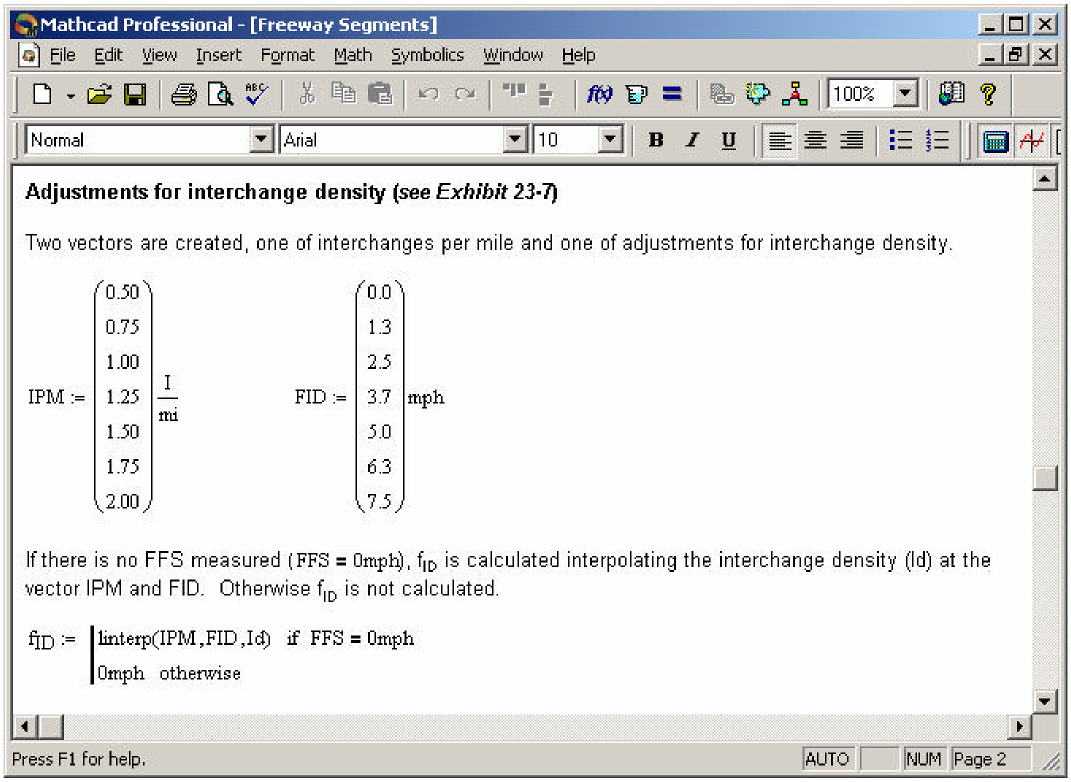
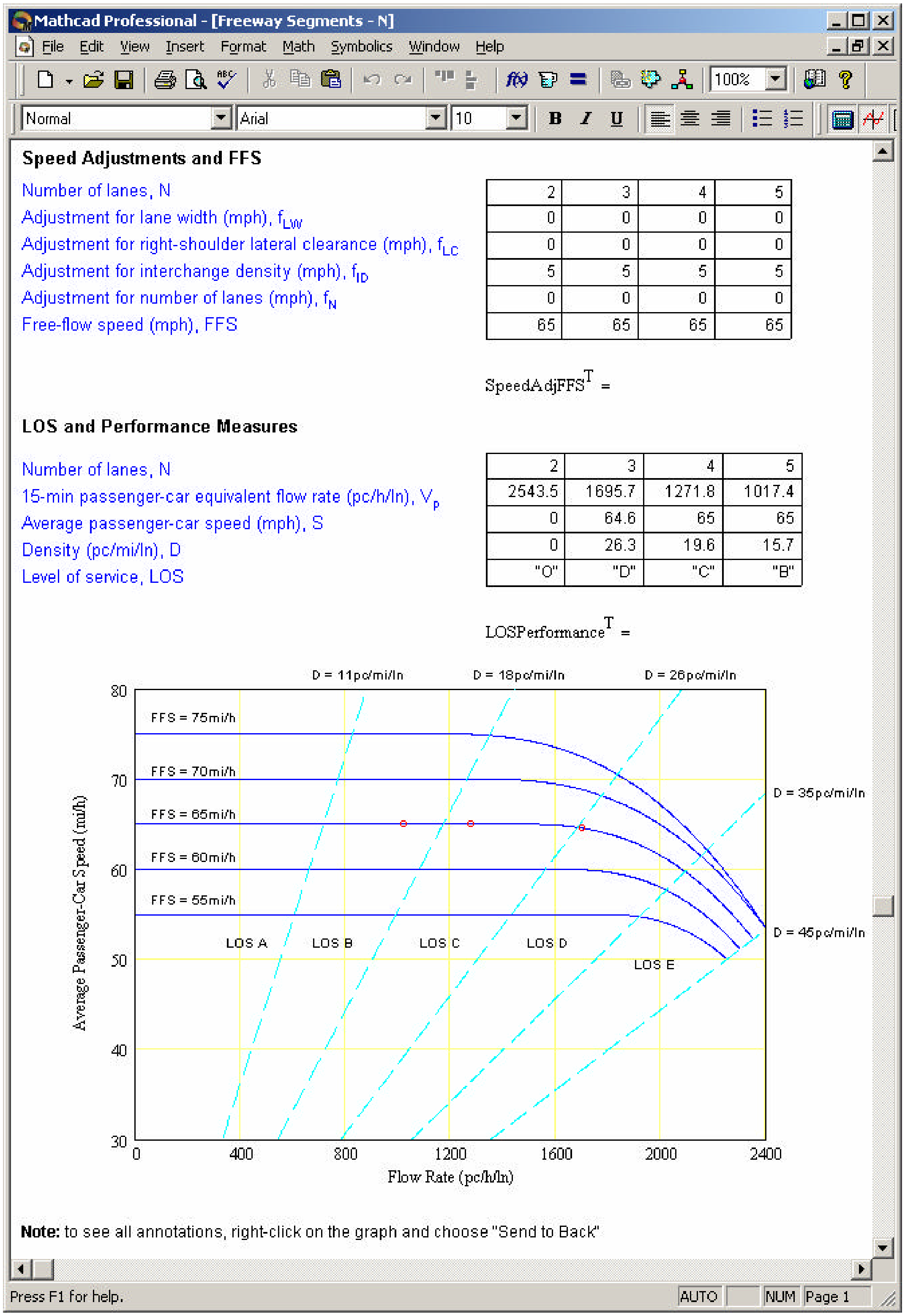


Figure 38. Adjustments for interchange density in the Basic Freeway Segments worksheet

New worksheets were developed to perform three types of analyses separately: operational and planning of level of service (LOS), design and planning of number of lanes required (N), and design and planning of flow rate achievable (v_p). An advantage in the design analysis, for example, is that the new worksheets perform the necessary iterations to compute a final result given a desired parameter. This approach eliminates the manual iterations performed by the user in the HCM worksheet (Barbara Ostrom and Abdul-Rahman Hamad, personal communication). Figure 39 shows the output of the worksheet that performs the design and planning of N. This figure shows an example where the number of lanes required to provide a LOS B is calculated. The table and the graph summarize the performance measures and the LOS of the freeway segment for each iteration.



Mathcad Professional - [Freeway Segments - N]

Speed Adjustments and FFS

Number of lanes, N	2	3	4	5
Adjustment for lane width (mph), f_{LW}	0	0	0	0
Adjustment for right-shoulder lateral clearance (mph), f_{LC}	0	0	0	0
Adjustment for interchange density (mph), f_{ID}	5	5	5	5
Adjustment for number of lanes (mph), f_N	0	0	0	0
Free-flow speed (mph), FFS	65	65	65	65

$SpeedAdjFFS^T =$

LOS and Performance Measures

Number of lanes, N	2	3	4	5
15-min passenger-car equivalent flow rate (pc/h/ln), V_p	2543.5	1695.7	1271.8	1017.4
Average passenger-car speed (mph), S	0	64.6	65	65
Density (pc/mi/ln), D	0	26.3	19.6	15.7
Level of service, LOS	"O"	"D"	"C"	"B"

$LOSPerformance^T =$

Note: to see all annotations, right-click on the graph and choose "Send to Back"

Press F1 for help. AUTO NUM Page 1

Figure 39. Worksheet that performs the design and planning of N

Examples

Example 4.1, Operational (LOS) (Example Problem 1, Chapter 23 – Basic Freeway Segments, HCM (2,000))

The freeway: existing four-lane freeway, rural area, very restricted geometry, rolling terrain, 70 mi/h speed limit.

The question: what is the LOS during the peak hour?

The facts:

- Two lanes in each direction
- 11 ft lane width
- 2 ft lateral clearance
- Commuter traffic
- 2,000 veh/h peak-hour volume (one direction)
- 5 percent trucks
- 0.95 PHF
- 1 interchange per mile
- Rolling terrain

Comments:

- Assume 0 percent buses and RVs since none are indicated.
- Assume BFFS of 75 mi/h for rural areas.
- Assume that the number of lanes does not affect free-flow speed, since the freeway is in rural area.
- Assume f_p = 1.00 for commuter traffic.

Solution: the solution to the example is shown in Figures 40 and 41.

Example 4.2, Design (N) (Example Problem 2, Chapter 23 – Basic Freeway Segments, HCM (2,000))

The freeway: new suburban freeway is being designed.

The question: how many lanes are needed to provide LOS B during the peak hour? (The HCM example specifies a LOS D. Here the LOS was changed to B to better show the iterative procedure used in the Mathcad worksheet).

The facts:

- 4,000 veh/h (one direction)
- 0.85 PHF
- Level terrain
- 1.50 interchanges per mile
- 15 percent trucks
- 3 percent RVs
- 12 ft lane width
- 6 ft lateral clearance

Comments:

- Assume commuter traffic. Thus, $f_p = 1.00$.
- Assume BFFS of 70 mi/h.
- Assume that the number of lanes affects free-flow speed, since the freeway is being designed in a suburban area.

Solution: the solution to the example is shown in Figures 42 and 43.

Example 4.3, Planning (V_p) (Example Problem 3, Chapter 23 – Basic Freeway Segments, HCM (2,000))

The freeway: existing six-lane freeway in a growing urban area.

The question: when should a fourth lane be added in each direction to avoid an excess of demand over capacity?

The facts:

- Level terrain
- 10 percent trucks
- 6 lanes
- 0.95 PHF
- Beyond 3 years, traffic grows at 4 percent per year
- FFS = 70 mi/h (measured in field)

Comments:

- Since no information is given on possible changes over time, assume that 10 percent trucks, PHF, and FFS remain constant.
- This problem deals with a variety of demand levels and can most easily be solved by computing the maximum volume that can be accommodated for each level of service.
- Assume 0 percent buses and RVs.
- Assume commuter traffic.

Solution: the solution to the example is shown in Figures 44 and 45.

The output results computed by the Mathcad worksheets compares perfectly with those calculated in the examples of the Highway Capacity Manual.

Basic Freeway Segments Worksheet
Level of Service (LOS)

General Information

Analyst:	Analyst
Agency or Company:	Agency or Company
Date Performed:	Date Performed
Analysis Time Period:	Analysis Time Period
Type of analysis:	(•) Design ( ) Planning

Site Information

Highway/Direction of Travel:	Highway/Direction
From/To:	From/To
Jurisdiction:	Jurisdiction
Analysis Year:	Analysis Year
Freeway segment area:	(•) Rural ( ) Urban

Flow Inputs

Volume:	$V := 2000 \frac{veh}{hr}$
Annual avg. daily traffic[1]:	$ADDT := 0 \frac{veh}{day}$
Peak-hour proportion of ADDT:	$K := 0$
Peak-hour direction proportion:	$D := 0$
Peak-hour factor:	$PHF := 0.92$
% Trucks and buses:	$P_T := 5$
% RVs:	$P_R := 0$
General terrain:	Rolling
Grade:	None
	$Length := 0mi$
	$UpDown := 0\%$

Directional design-hour volume:

$DDHV := ADDT \cdot K \cdot D \cdot \frac{day}{hr}$ $DDHV = 0 \frac{veh}{hr}$

Driver type: (•) Commuter/Weekday ( ) Recreational/Weekend

Note: 1. If ADDT is not provided, v_p is computed using V. Otherwise v_p is computed using DDHV.

Calculate Flow Adjustments

Driver population factor:	$f_p := 1$
Passenger-car equivalents for truck/buses:	$E_T = 2.5$
Passenger-car equivalents for RVs:	$E_R = 2$
Heavy-vehicle adjustment factor: $f_{HV} := \frac{1}{1 + P_T \cdot (E_T - 1) + P_R \cdot (E_R - 1)}$	$f_{HV} = 0.93$

Speed Inputs

Lane width	$Lw := 11ft$
Rt.-shoulder lateral clearance	$Rslc := 2ft$
Interchange density	$Id := 1 \frac{I}{mi}$
Number of lanes	$N := 2$
Free-flow speed (measured)	$FFS := 0mph$
Base free-flow speed	$BFFS := 75mph$

Figure 40. Example 4.1

Calculate Speed Adjustments and FFS

Adjustment for Lane Width (Exhibit 23-4): $f_{LW} = 1.9\,\text{mph}$

Adjustment for Right-Shoulder Lateral Clearance (Exhibit 23-5): $f_{LC} = 2.4\,\text{mph}$

Adjustment for Interchange Density (Exhibit 23-7): $f_{ID} = 2.5\,\text{mph}$

Adjustment for Number of Lanes (Exhibit 23-6): $f_N = 0\,\text{mph}$

$FSS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N$ $FFS = 68.2\,\text{mph}$

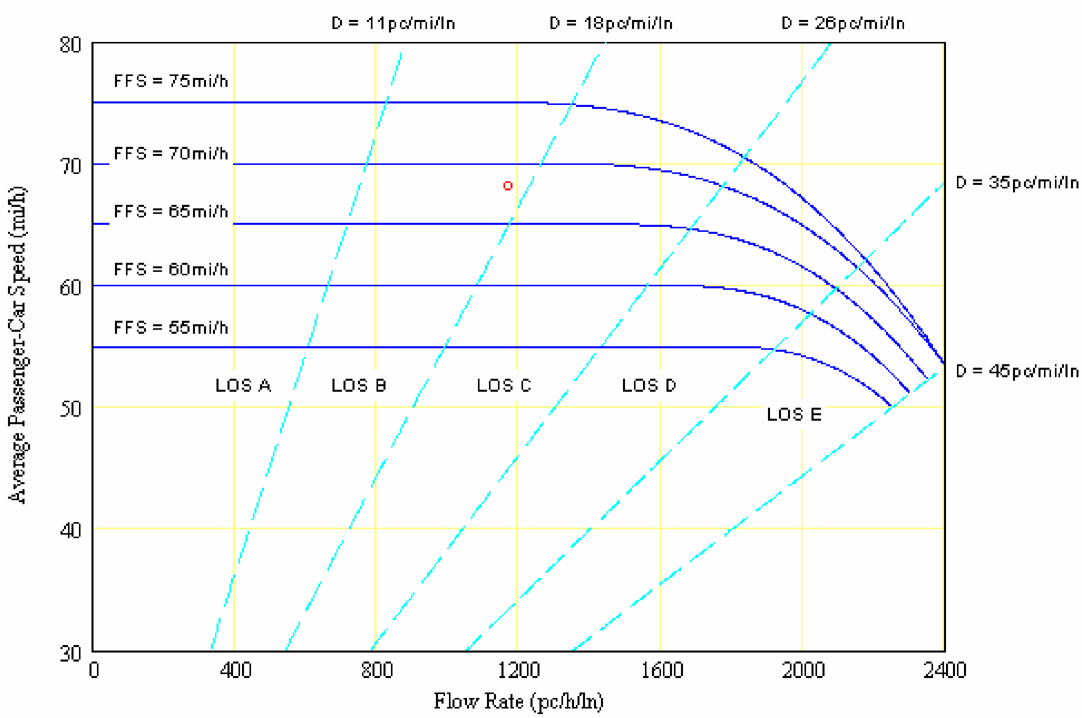
LOS and Performance Measures

Flow rate: $V_p = \dfrac{VorDDHV}{PHF \cdot N \cdot f_{HV} \cdot f_p}$ $V_p = 1168\,\dfrac{pc}{hr \cdot ln}$

Average passenger-car speed: $S = 68.2\,\text{mph}$

Density: $D := \dfrac{V_p}{S}$ $D = 17.1\,\dfrac{pc}{mi \cdot ln}$

Level of service: LOS = "B"



Note: to see all annotations, right-click on the graph and choose "Send to Back"

Figure 41. Example 4.1 (contd.)

Basic Freeway Segments Worksheet
Number of Lanes Required (N)

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analysis Time Period: Analysis Time Period

Site Information

Highway/Direction of Travel: Highway/Direction
From/To: From/To
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year
Freeway segment area: ○ Rural ◉ Urban

Type of analysis: ◉ Design ○ Planning

Minimum LOS desired: B

Flow Inputs

Volume: $V := 4000 \frac{veh}{hr}$

Annual avg. daily traffic[1]: $ADDT := 0 \frac{veh}{day}$

Peak-hour proportion of ADDT: $K := 0$

Peak-hour direction proportion: $D := 0$

Directional design-hour volume:

$DDHV := ADDT \cdot K \cdot D \cdot \frac{day}{hr}$ $\quad DDHV = 0 \frac{veh}{hr}$

Driver type: ◉ Commuter/Weekday ○ Recreational/Weekend

Peak-hour factor: $PHF := 0.85$

% Trucks and buses: $P_T := 15$

% RVs: $P_R := 3$

General terrain: Level

Grade: None

$Length := 0mi$

$UpDown := 0\%$

Note: 1. If ADDT is not provided, v_p is computed using V. Otherwise v_p is computed using DDHV.

Calculate Flow Adjustments

Driver population factor: $f_p := 1$

Passenger-car equivalents for truck/buses: $E_T = 1.5$

Passenger-car equivalents for RVs: $E_R = 1.2$

Heavy-vehicle adjustment factor: $f_{HV} := \frac{1}{1 + P_T \cdot (E_T - 1) + P_R \cdot (E_R - 1)}$ $\quad f_{HV} = 0.925$

Speed Inputs

Lane width: $Lw := 12ft$
Rt.-shoulder lateral clearance: $Rslc := 6ft$
Interchange density: $Id := 1.5 \frac{I}{mi}$
Free-flow speed (measured): $FFS := 0mph$
Base free-flow speed: $BFFS := 70mph$

Figure 42. Example 4.2

Speed Adjustments and FFS

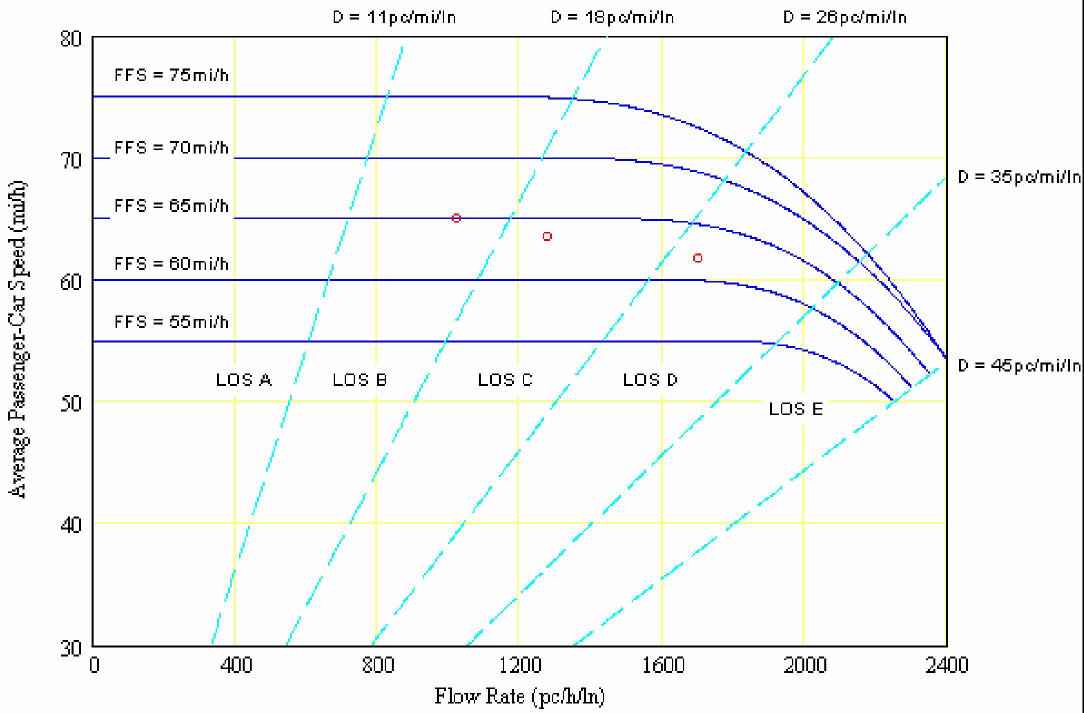
Number of lanes, N	2	3	4	5
Adjustment for lane width (mph), f_{LW}	0	0	0	0
Adjustment for right-shoulder lateral clearance (mph), f_{LC}	0	0	0	0
Adjustment for interchange density (mph), f_{ID}	5	5	5	5
Adjustment for number of lanes (mph), f_N	4.5	3	1.5	0
Free-flow speed (mph), FFS	60.5	62	63.5	65

$SpeedAdjFFS^T =$

LOS and Performance Measures

Number of lanes, N	2	3	4	5
15-min passenger-car equivalent flow rate (pc/h/ln), V_p	2543.5	1695.7	1271.8	1017.4
Average passenger-car speed (mph), S	0	61.8	63.5	65
Density (pc/mi/ln), D	0	27.4	20	15.7
Level of service, LOS	"O"	"D"	"C"	"B"

$LOSPerformance^T =$



Note: to see all annotations, right-click on the graph and choose "Send to Back"

Figure 43. Example 4.2 (contd.)

Basic Freeway Segments Worksheet
Flow Rate Achievable (V_p)

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analysis Time Period: Analysis Time Period

Type of analysis: ○ Design ◉ Planning

Site Information

Highway/Direction of Travel: Highway/Direction
From/To: From/To
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year
Freeway segment area: ○ Rural ◉ Urban

Flow Inputs

Peak-hour factor: $PHF := 0.95$

% Trucks and buses: $P_T := 10$

% RVs: $P_R := 0$

General terrain: Level

Grade: None

$Length := 0mi$

$UpDown := 0\%$

Driver type: ◉ Commuter/Weekday ○ Recreational/Weekend

Calculate Flow Adjustments

Driver population factor: $f_p := 1$

Passenger-car equivalents for truck/buses: $E_T = 1.5$

Passenger-car equivalents for RVs: $E_R = 1.2$

Heavy-vehicle adjustment factor: $f_{HV} := \dfrac{1}{1 + P_T \cdot (E_T - 1) + P_R \cdot (E_R - 1)}$ $f_{HV} = 0.952$

Speed Inputs

Lane width: $Lw := 0ft$
Rt.-shoulder lateral clearance: $Rslc := 0ft$
Interchange density: $Id := 0 \dfrac{I}{mi}$
Number of lanes: $N := 3$
Free-flow speed (measured): $FFS := 70mph$
Base free-flow speed: $BFFS := 0mph$

Figure 44. Example 4.3

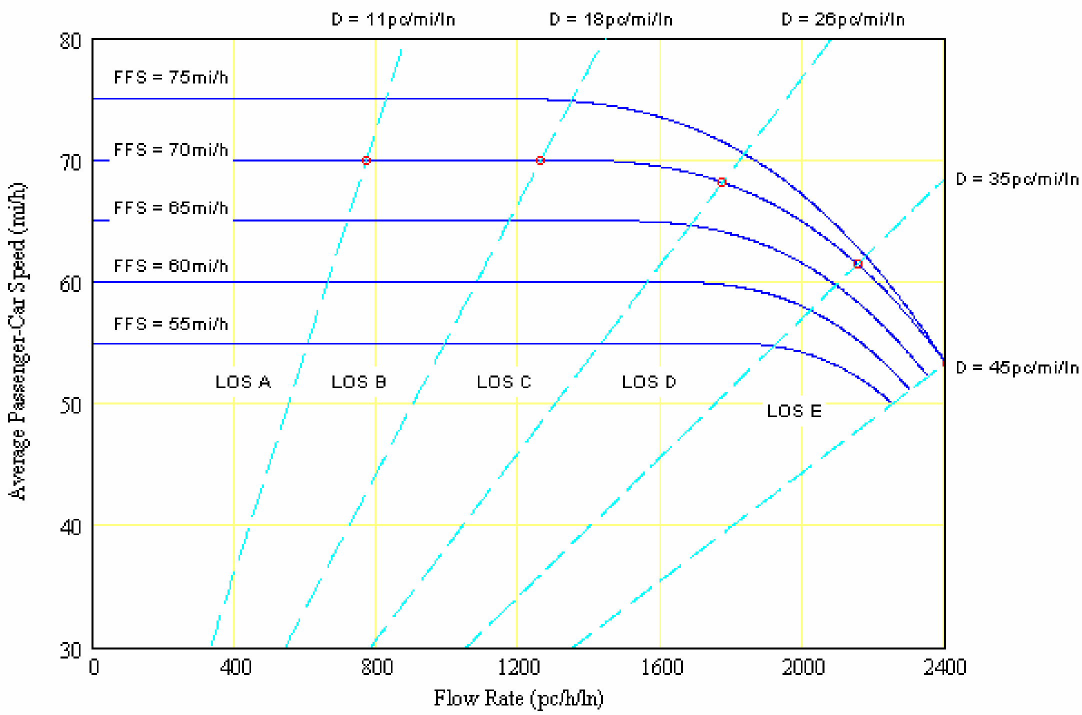
Calculate Speed Adjustments and FFS

Adjustment for Lane Width (Exhibit 23-4):	f_{LW} = 0 mph
Adjustment for Right-Shoulder Lateral Clearance (Exhibit 23-5):	f_{LC} = 0 mph
Adjustment for Interchange Density (Exhibit 23-7):	f_{ID} = 0 mph
Adjustment for Number of Lanes (Exhibit 23-6):	f_N = 0 mph
FSS = BFFS - f_{LW} - f_{LC} - f_{ID} - f_N	FFS = 70 mph

LOS and Performance Measures

Level of service, LOS	"A"	"B"	"C"	"D"	"E"
Maximum service flow rate (pc/h/ln), V_p	770	1260	1770	2150	2400
Volume (veh/h), V	2090	3420	4804.3	5835.7	6514.3
Average passenger-car speed (mph), S	70	70	68.2	61.5	53.3
Density (pc/mi/ln), D	11	18	26	35	45

Results =



Note: to see all annotations, right-click on the graph and choose "Send to Back"

Figure 45. Example 4.3 (contd.)

CHAPTER 5

RAMPS AND RAMPS JUNCTIONS

Several additional parameters shown in Figure 46 were added to the Input section of the worksheet to replace the ramp diagram used in the HCM worksheet. These new variables are the inner and outer acceleration lanes lengths and the inner and outer deceleration lanes lengths. For single-lane ramps, only the inner lanes are used. Also, the user must specify via radio buttons the side location of the ramp and whether the ramp is located in merge or diverge areas.

In the results portion of the worksheet shown in Figure 47 the variables have an additional subscript that indicates whether the variable corresponds to the Merge Areas section (*m*) or the Diverge Areas section (*d*).

Examples

Example 5.1 (Example Problem 1, Chapter 25 – Ramps and Ramp Junctions, HCM (2,000))

The ramp: an isolated on-ramp (single lane) to a four-lane freeway.

The question: what is the LOS during the peak hour?

The facts:

- Isolated location
- 12 ft lane width on freeway
- 0 percent RVs
- Ramp volume = 550 veh/h
- 10 percent trucks on freeway
- Acceleration lane length = 740 ft
- One lane ramp
- Level terrain
- Adequate lateral clearances
- FFS = 60 mi/h for freeway
- 5 percent trucks on ramp
- Freeway volume = 2,500 veh/h

- FFS = 45 mi/h for ramp
- Two lane (in one direction) freeway segment
- PHF = 0.90
- Drivers are regular commuters

Comments:

- Use the Basic Freeway Segments Chapter to identify f_{HV} and f_p.

Solution: the solution to the example is shown in Figures 48 and 49.

Example 5.2 (Example Problem 2 Part I, Chapter 25 – Ramps and Ramp Junctions, HCM (2,000))

The ramp: an off-ramp (single-lane) pair, 750 ft apart, from a six-lane freeway. The length of the first deceleration lane is 500 ft.

The question: what is the LOS during the peak hour for the first off-ramp?

The facts:

- One lane off-ramps
- FFS = 60 mi/h for freeway
- Rolling terrain
- PHF = 0.95
- Three lane (in one direction) freeway segment
- 0 percent RVs
- Drivers are regular commuters
- FFS = 40 mi/h for first off-ramp
- Freeway volume = 4,500 veh/h
- First off-ramp volume = 300 veh/h
- 5 percent trucks on freeway and off-ramps

Comments:

- Use the Basic Freeway Segments Chapter to identify f_{HV} and f_p.

Solution: the solution to the example is shown in Figures 50 and 51.

The output results computed by the Mathcad worksheets compares perfectly with those calculated in the examples of the Highway Capacity Manual.

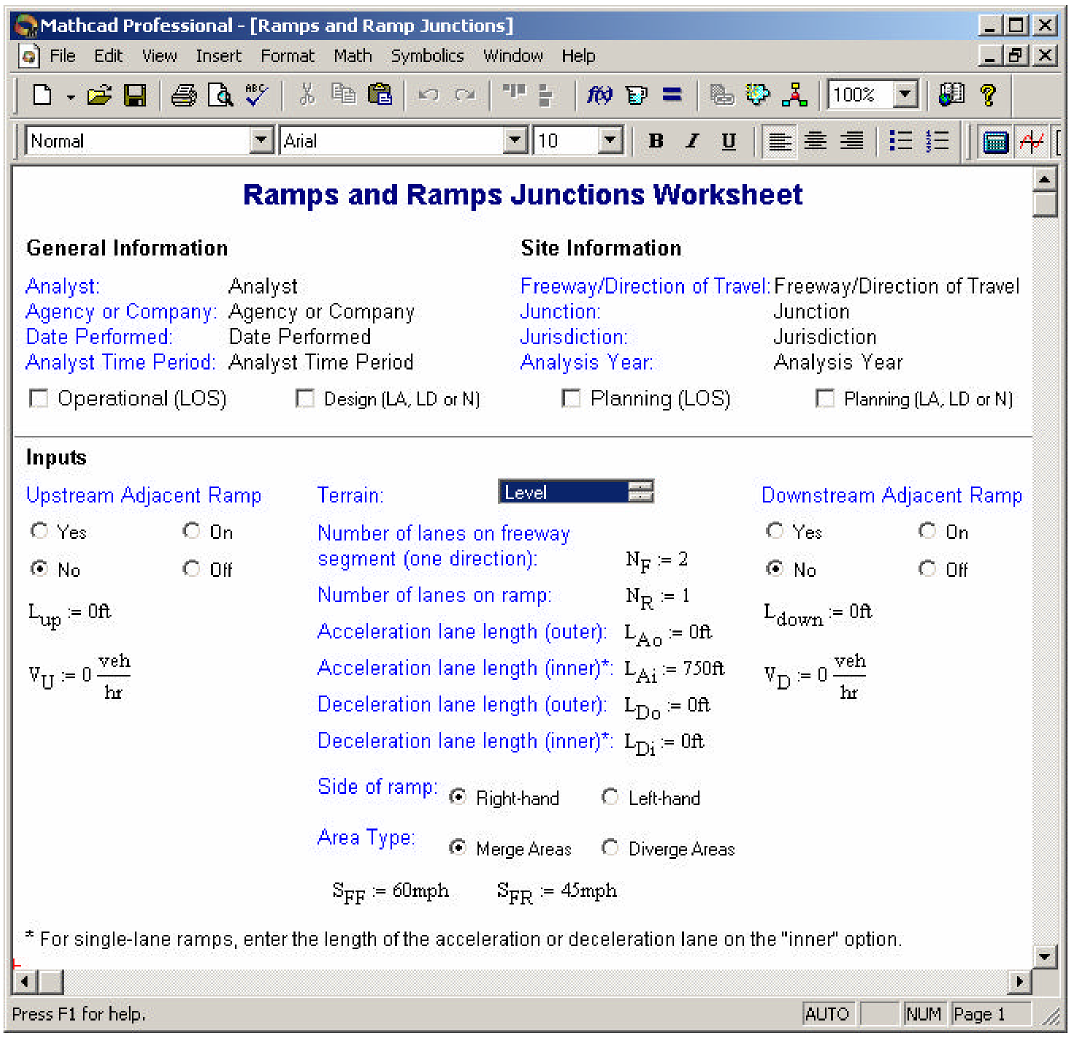


Figure 46. Input section of the Ramps and Ramps Junctions worksheet

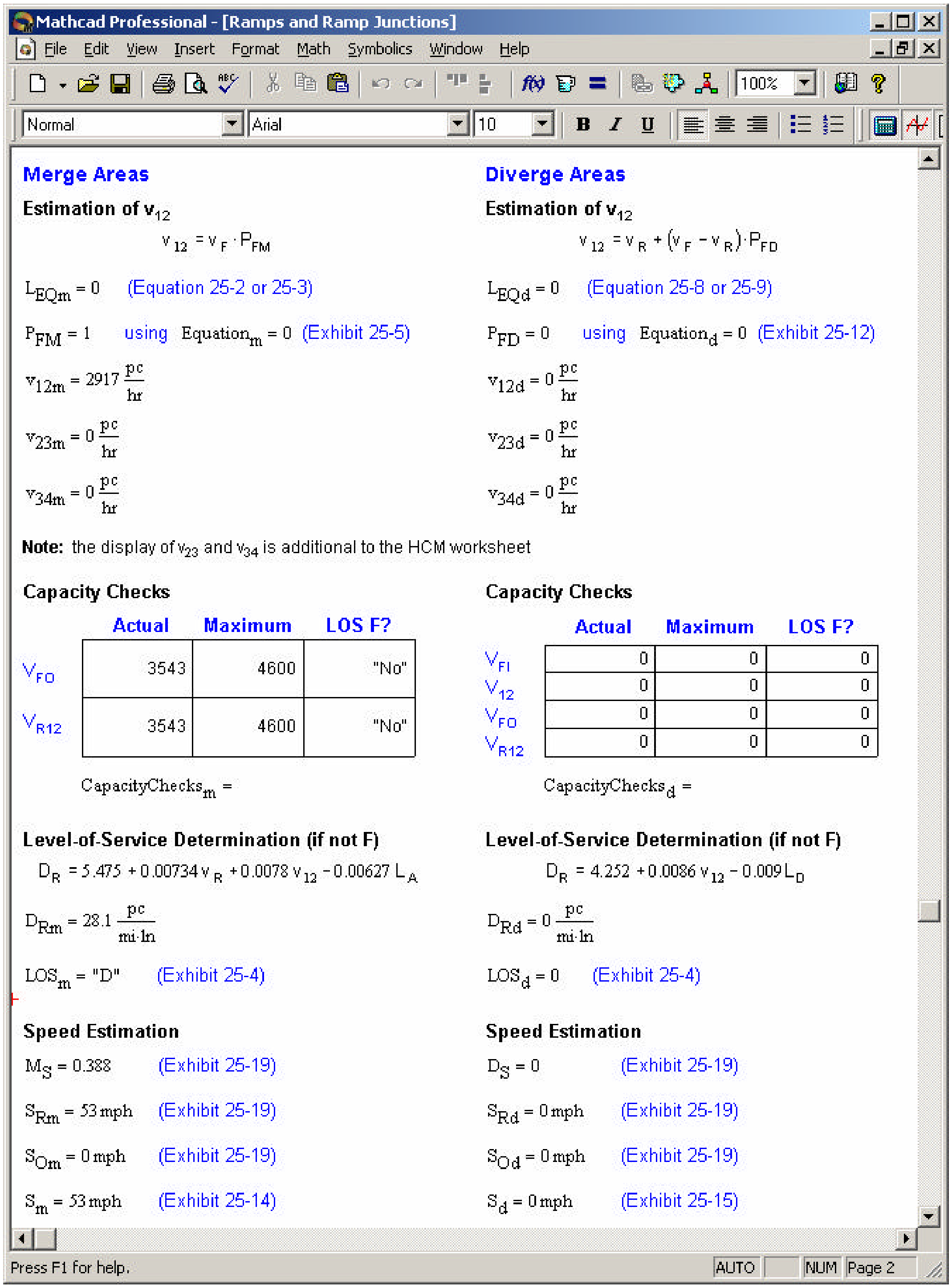


Figure 47. Lower part of the Ramps and Ramps Junctions worksheet

Ramps and Ramps Junctions Worksheet

General Information

Analyst: Analyst
Agency or Company: Agency or Company
Date Performed: Date Performed
Analyst Time Period: Analyst Time Period

Site Information

Freeway/Direction of Travel: Freeway/Direction of Travel
Junction: Junction
Jurisdiction: Jurisdiction
Analysis Year: Analysis Year

☑ Operational (LOS) ☐ Design (LA, LD or N) ☐ Planning (LOS) ☐ Planning (LA, LD or N)

Inputs

Upstream Adjacent Ramp

○ Yes ○ On
◉ No ○ Off

$L_{up} := 0ft$

$V_U := 0 \frac{veh}{hr}$

Terrain: Level

Number of lanes on freeway segment (one direction): $N_F := 2$

Number of lanes on ramp: $N_R := 1$

Acceleration lane length (outer): $L_{Ao} := 0ft$

Acceleration lane length (inner)*: $L_{Ai} := 750ft$

Deceleration lane length (outer): $L_{Do} := 0ft$

Deceleration lane length (inner)*: $L_{Di} := 0ft$

Side of ramp: ◉ Right-hand ○ Left-hand

Area Type: ◉ Merge Areas ○ Diverge Areas

$S_{FF} := 60mph$ $S_{FR} := 45mph$

Downstream Adjacent Ramp

○ Yes ○ On
◉ No ○ Off

$L_{down} := 0ft$

$V_D := 0 \frac{veh}{hr}$

* For single-lane ramps, enter the length of the acceleration or deceleration lane on the "inner" option.

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	%HV	f_p
v_F	0	0	0	2500	0.9	10	1
v_R	0	0	0	550	0.9	5	1
v_U	0	0	0	0	0	0	0
v_D	0	0	0	0	0	0	0

(pc/h)	f_{HV}	v (pc/h)
v_F	0.952	2917
v_R	0.976	626
v_U	0	0
v_D	0	0

Results =

Note: f_{HV} and v cannot be displayed in the same table along with the rest of the parameters (as in the HCM worksheet), because f_{HV} and v depend on those parameters.

Figure 48. Example 5.1

Merge Areas

Estimation of v_{12}

$$v_{12} = v_F \cdot P_{FM}$$

$L_{EQm} = 0$ (Equation 25-2 or 25-3)

$P_{FM} = 1$ using $\text{Equation}_m = 0$ (Exhibit 25-5)

$v_{12m} = 2917 \frac{pc}{hr}$

$v_{23m} = 0 \frac{pc}{hr}$

$v_{34m} = 0 \frac{pc}{hr}$

Diverge Areas

Estimation of v_{12}

$$v_{12} = v_R + (v_F - v_R) \cdot P_{FD}$$

$L_{EQd} = 0$ (Equation 25-8 or 25-9)

$P_{FD} = 0$ using $\text{Equation}_d = 0$ (Exhibit 25-12)

$v_{12d} = 0 \frac{pc}{hr}$

$v_{23d} = 0 \frac{pc}{hr}$

$v_{34d} = 0 \frac{pc}{hr}$

Note: the display of v_{23} and v_{34} is additional to the HCM worksheet

Capacity Checks (Merge)

	Actual	Maximum	LOS F?
V_{FO}	3543	4600	"No"
V_{R12}	3543	4600	"No"

$\text{CapacityChecks}_m =$

Capacity Checks (Diverge)

	Actual	Maximum	LOS F?
V_{FI}	0	0	0
V_{12}	0	0	0
V_{FO}	0	0	0
V_{R12}	0	0	0

$\text{CapacityChecks}_d =$

Level-of-Service Determination (if not F)

$$D_R = 5.475 + 0.00734\, v_R + 0.0078\, v_{12} - 0.00627\, L_A$$

$D_{Rm} = 28.1 \frac{pc}{mi \cdot ln}$

$LOS_m = \text{"D"}$ (Exhibit 25-4)

Level-of-Service Determination (if not F)

$$D_R = 4.252 + 0.0086\, v_{12} - 0.009\, L_D$$

$D_{Rd} = 0 \frac{pc}{mi \cdot ln}$

$LOS_d = 0$ (Exhibit 25-4)

Speed Estimation

$M_S = 0.388$ (Exhibit 25-19)

$S_{Rm} = 53\, mph$ (Exhibit 25-19)

$S_{Om} = 0\, mph$ (Exhibit 25-19)

$S_m = 53\, mph$ (Exhibit 25-14)

Speed Estimation

$D_S = 0$ (Exhibit 25-19)

$S_{Rd} = 0\, mph$ (Exhibit 25-19)

$S_{Od} = 0\, mph$ (Exhibit 25-19)

$S_d = 0\, mph$ (Exhibit 25-15)

Figure 49. Example 5.1 (contd.)

Ramps and Ramps Junctions Worksheet

General Information

Analyst:	Analyst
Agency or Company:	Agency or Company
Date Performed:	Date Performed
Analyst Time Period:	Analyst Time Period

Site Information

Freeway/Direction of Travel:	Freeway/Direction of Travel
Junction:	Junction
Jurisdiction:	Jurisdiction
Analysis Year:	Analysis Year

☑ Operational (LOS) ☐ Design (LA, LD or N) ☐ Planning (LOS) ☐ Planning (LA, LD or N)

Inputs

Upstream Adjacent Ramp

○ Yes ○ On

◉ No ○ Off

$L_{up} := 0ft$

$V_U := 0 \frac{veh}{hr}$

Terrain: Rolling

Number of lanes on freeway segment (one direction): $N_F := 3$

Number of lanes on ramp: $N_R := 1$

Acceleration lane length (outer): $L_{Ao} := 0ft$

Acceleration lane length (inner)*: $L_{Ai} := 0ft$

Deceleration lane length (outer): $L_{Do} := 0ft$

Deceleration lane length (inner)*: $L_{Di} := 500ft$

Side of ramp: ◉ Right-hand ○ Left-hand

Area Type: ○ Merge Areas ◉ Diverge Areas

$S_{FF} := 60mph$ $S_{FR} := 40mph$

Downstream Adjacent Ramp

◉ Yes ○ On

○ No ◉ Off

$L_{down} := 750ft$

$V_D := 500 \frac{veh}{hr}$

* For single-lane ramps, enter the length of the acceleration or deceleration lane on the "inner" option.

Conversion to pc/h Under Base Conditions

(pc/h)	AADT (veh/day)	K	D	V (veh/h)	PHF	%HV	f_p
v_F	0	0	0	4500	0.95	5	1
v_R	0	0	0	300	0.95	5	1
v_U	0	0	0	0	0	0	0
v_D	0	0	0	500	0.95	5	1

(pc/h)	f_{HV}	v (pc/h)
v_F	0.93	5092
v_R	0.93	339
v_U	0	0
v_D	0.93	566

Results =

Note: f_{HV} and v cannot be displayed in the same table along with the rest of the parameters (as in the HCM worksheet), because f_{HV} and v depend on those parameters.

Figure 50. Example 5.2

Merge Areas

Estimation of v_{12}

$$v_{12} = v_F \cdot P_{FM}$$

$L_{EQm} = 0$ (Equation 25-2 or 25-3)

$P_{FM} = 0$ using $\text{Equation}_m = 0$ (Exhibit 25-5)

$v_{12m} = 0 \frac{pc}{hr}$

$v_{23m} = 0 \frac{pc}{hr}$

$v_{34m} = 0 \frac{pc}{hr}$

Diverge Areas

Estimation of v_{12}

$$v_{12} = v_R + (v_F - v_R) \cdot P_{FD}$$

$L_{EQd} = 657$ (Equation 25-8 or 25-9)

$P_{FD} = 0.617$ using $\text{Equation}_d = 5$ (Exhibit 25-12)

$v_{12d} = 3272 \frac{pc}{hr}$

$v_{23d} = 0 \frac{pc}{hr}$

$v_{34d} = 0 \frac{pc}{hr}$

Note: the display of v_{23} and v_{34} is additional to the HCM worksheet

Capacity Checks (Merge)

	Actual	Maximum	LOS F?
V_{FO}	0	0	0
V_{R12}	0	0	0

$\text{CapacityChecks}_m =$

Capacity Checks (Diverge)

	Actual	Maximum	LOS F?
V_{FI}	5092	6900	"No"
V_{12}	3272	4400	"No"
V_{FO}	4753	6900	"No"
V_{R12}	339	2100	"No"

$\text{CapacityChecks}_d =$

Level-of-Service Determination (if not F) (Merge)

$$D_R = 5.475 + 0.00734\, v_R + 0.0078\, v_{12} - 0.00627\, L_A$$

$D_{Rm} = 0 \frac{pc}{mi \cdot ln}$

$LOS_m = 0$ (Exhibit 25-4)

Level-of-Service Determination (if not F) (Diverge)

$$D_R = 4.252 + 0.0086\, v_{12} - 0.009\, L_D$$

$D_{Rd} = 27.9 \frac{pc}{mi \cdot ln}$

$LOS_d = \text{"C"}$ (Exhibit 25-4)

Speed Estimation (Merge)

$M_S = 0$ (Exhibit 25-19)

$S_{Rm} = 0$ mph (Exhibit 25-19)

$S_{Om} = 0$ mph (Exhibit 25-19)

$S_m = 0$ mph (Exhibit 25-14)

Speed Estimation (Diverge)

$D_S = 0.394$ (Exhibit 25-19)

$S_{Rd} = 52.9$ mph (Exhibit 25-19)

$S_{Od} = 62.6$ mph (Exhibit 25-19)

$S_d = 56$ mph (Exhibit 25-15)

Figure 51. Example 5.2 (contd.)

CHAPTER 6

TRANSIT

The HCM does not provide a worksheet to perform the calculations for this chapter. Thus, the Mathcad worksheet was developed following the organization of the chapter and solving the examples provided in the HCM.

The worksheet is divided in two main sections: Bus Facilities and Light Rail and Streetcar Facilities. Within the Bus Facilities section, there are four subsections: Dwell Time, Bus Vehicle Capacity, Bus Person Capacity and Average Speed of Buses. List boxes were used to select many of the inputs including the Bus type and Location of doors or channels as shown in Figure 52. Each subsection contains its own input parameters, computational procedure, and output display.

In the Light Rail and Streetcar Facilities section, the inputs were divided in four parts: General Inputs, Dwell Time Inputs, Minimum Headways Inputs and Light Rail and Streetcar Capacity Inputs using the Parameters section the HCM as a guide.

Examples

Example 6.1 (Example Problem 1, Chapter 27 – Transit, HCM (2,000))

<u>The situation:</u> an express route is planned along an arterial from a suburb to the CBD with 10 stops, including one at a transit center midway (Stop 5). The route will operate in mixed traffic in the CBD (Stops 7 to 10).

<u>The question:</u> what will the average dwell times be at the 10 stops?

<u>The facts:</u>

- The route will use 42-seat buses
- Exact fare is required on boarding
- The door opening and closing time is 4 s

- All passengers board through the front door and alight through the back door
- The transit agency has estimated potential ridership for the route and predicts the following average number of boarding and alighting passengers per stop.

Stop number	1	2	3	4	5	6	7	8	9	10
Alighting passengers	0	0	3	2	14	6	16	19	15	11
Boarding passengers	20	16	11	12	16	8	2	1	0	0

Comments:

- Assume 3.0 s boarding time per passenger (3.5 s with standees)
- Assume 2.0 s alighting time per passenger

Solution: the solution to the example is shown in Figure 53.

The output results computed by the Mathcad worksheets compares perfectly with those calculated in the example of the Highway Capacity Manual.

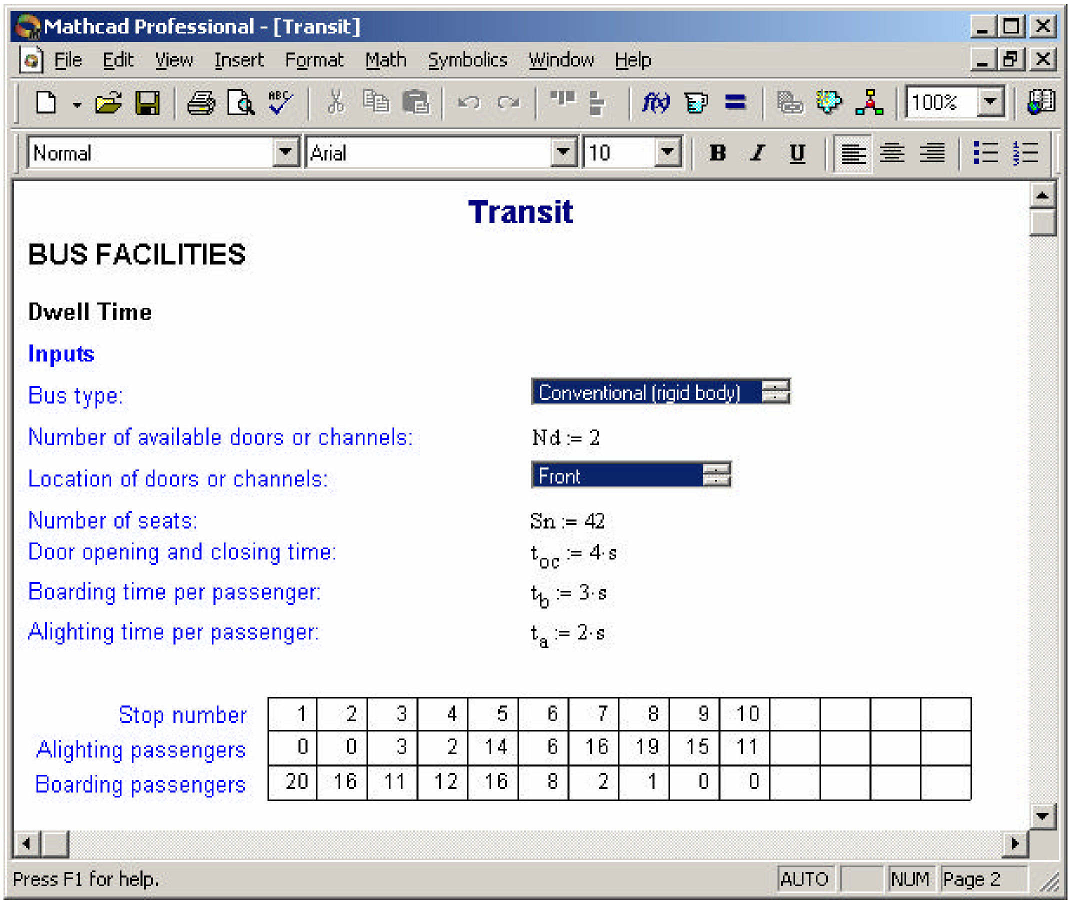


Figure 52. Upper part of the Transit worksheet

Transit

BUS FACILITIES

Dwell Time

Inputs

Bus type: Conventional (rigid body)

Number of available doors or channels: $Nd := 2$

Location of doors or channels: Front

Number of seats: $Sn := 42$

Door opening and closing time: $t_{oc} := 4 \cdot s$

Boarding time per passenger: $t_b := 3 \cdot s$

Alighting time per passenger: $t_a := 2 \cdot s$

Stop number	1	2	3	4	5	6	7	8	9	10				
Alighting passengers	0	0	3	2	14	6	16	19	15	11				
Boarding passengers	20	16	11	12	16	8	2	1	0	0				

Results

Results =

Stop number	1	2	3	4	5	6	7	8	9	10
Seated	20	36	42	42	42	42	42	26	11	0
Standees	0	0	2	12	14	16	2	0	0	0
Boarding time (s)	60	48	38.5	42	56	28	7	3	0	0
Alighting time (s)	0	0	6	4	28	12	32	38	30	22
Dwell time (s)	64	52	42.5	46	60	32	36	42	34	26

Figure 53. Example 6.1

CHAPTER 7

SENSITIVITY ANALYSIS

One of the benefits that the dynamic Mathcad worksheets offer over the traditional static documents is the ability to explore the sensitivity of the procedures to varying equations. Two examples are presented to demonstrate how the user can perform this type of analysis.

Example 7.1 (Basic Freeway Segments)

Using the same freeway conditions of Example 4.1, the equation used to calculate the equivalent passenger-car flow rate, v_p (Equation 23-2, HCM (2000)), is multiplied by a factor of 2, and the new LOS and performance measures are compared with those calculated in Example 4.1.

Figures 54 and 55 show the original and the modified equation to compute v_p respectively. The modification is made by simply multiplying V by 2 as shown in Figure 55. Figures 56 and 57 show the LOS and performance measures calculated using the original and the modified equation respectively. It can be observed that the LOS drops from B to E after the modification.

15-min passenger-car equivalent flow rate (*see Equation 23-2*)

If the annual avg. daily traffic is not provided (ADDT = 0), v_p is computed using the hourly volume (V). Otherwise v_p is computed using the directional design-hour volume (DDHV), which is computed in the Flow Input section of the worksheet.

$$v_p := \begin{cases} \dfrac{V}{PHF \cdot N \cdot f_{HV} \cdot f_p} & \text{if } ADDT = 0 \\ \dfrac{DDHV}{PHF \cdot N \cdot f_{HV} \cdot f_p} & \text{otherwise} \end{cases}$$

Figure 54. Original equation to compute v_p

15-min passenger-car equivalent flow rate (see *Equation 23-2*)

If the annual avg. daily traffic is not provided (ADDT = 0), v_p is computed using the hourly volume (V). Otherwise v_p is computed using the directional design-hour volume (DDHV), which is computed in the Flow Input section of the worksheet.

$$v_p := \begin{cases} \dfrac{2 \cdot V}{PHF \cdot N \cdot f_{HV} \cdot f_p} & \text{if } ADDT = 0 \\ \dfrac{DDHV}{PHF \cdot N \cdot f_{HV} \cdot f_p} & \text{otherwise} \end{cases}$$

Figure 55. Modified equation to compute v_p

LOS and Performance Measures

Flow rate: $v_p = \dfrac{VorDDHV}{PHF \cdot N \cdot f_{HV} \cdot f_p}$ $\quad v_p = 1168 \dfrac{pc}{hr \cdot ln}$

Average passenger-car speed: $S = 68.2\,mph$

Density: $D := \dfrac{v_p}{S}$ $\quad D = 17.1 \dfrac{pc}{mi \cdot ln}$

Level of service: LOS = "B"

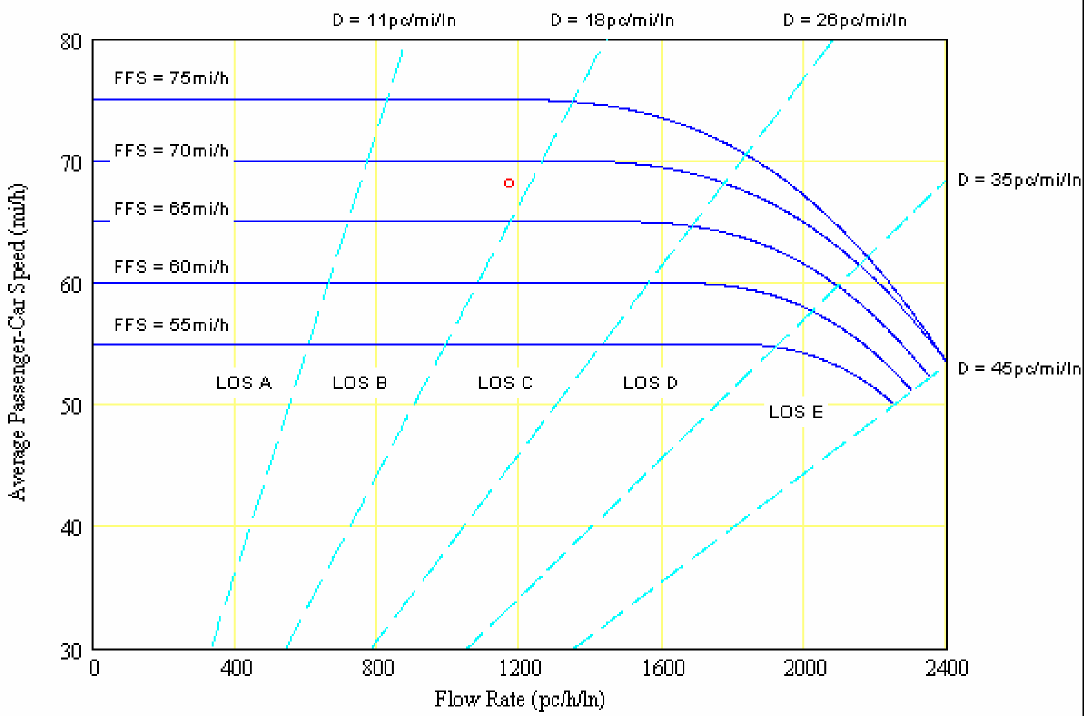


Figure 56. LOS and performance measures computed with the original equation of v_p

LOS and Performance Measures

Flow rate: $V_p = \frac{VorDDHV}{PHF \cdot N \cdot f_{HV} \cdot f_p}$ $\quad V_p = 2337 \frac{pc}{hr \cdot ln}$

Average passenger-car speed: $S = 54.6\,mph$

Density: $D := \frac{V_p}{S}$ $\quad D = 42.8 \frac{pc}{mi \cdot ln}$

Level of service: LOS = "E"

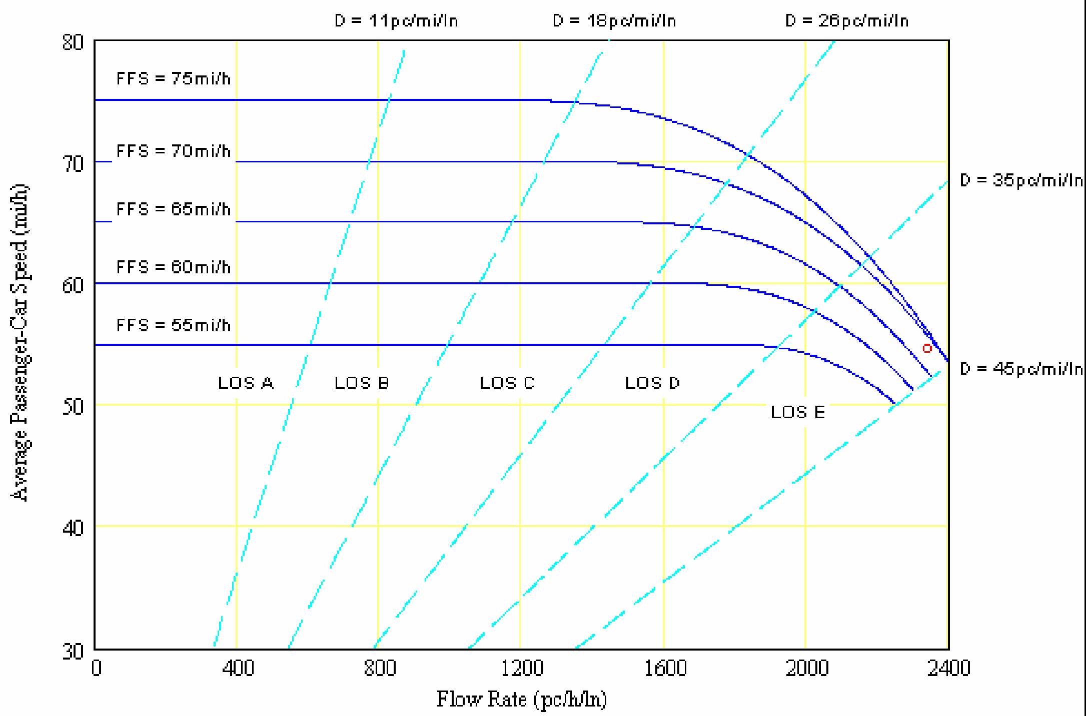


Figure 57. LOS and performance measures computed with the modified equation of v_p

Example 7.2 (Ramps and Ramp Junctions)

Using the same ramp conditions of Example 5.1, 1,000 pc/h are subtracted to the equation used to calculate the flow rate in Lanes 1 and 2 of freeway immediately upstream of merge, v_{12} (Equation of Exhibit 25-5, HCM (2000)). The new LOS and speed estimation are compared with those calculated in Example 5.1.

Figures 58 and 59 show the original and the modified equation to compute v_{12} respectively. Figures 60 and 61 show the LOS and speed estimation calculated using the original and the modified equation respectively. As shown in the figures the LOS improves from D to C and the space mean speed, S, increases from 53 mph to 54.5 mph.

It is important to note that in both examples the modifications are carried through the whole procedure and are reflected in intermediate and final results.

Flow rate in lanes 1 and 2 of freeway immediately upstream of merge (see Exhibit 25-5)

This equation is computed only for Merge Areas ($Area = 1$)

$$v_{12} := \begin{cases} v_F \cdot P_{FM} & \text{if } Area = 1 \\ 0 & \text{otherwise} \end{cases}$$

Figure 58. Original equation to compute v_{12}

Flow rate in lanes 1 and 2 of freeway immediately upstream of merge (see Exhibit 25-5)

This equation is computed only for Merge Areas ($Area = 1$)

$$v_{12} := \begin{cases} v_F \cdot P_{FM} - 1000 & \text{if } Area = 1 \\ 0 & \text{otherwise} \end{cases}$$

Figure 59. Modified equation to compute v_{12}

Merge Areas

Estimation of v_{12}

$$v_{12} = v_F \cdot P_{FM}$$

$L_{EQm} = 0$ (Equation 25-2 or 25-3)

$P_{FM} = 1$ using $Equation_m = 0$ (Exhibit 25-5)

$v_{12m} = 2917 \frac{pc}{hr}$

$v_{23m} = 0 \frac{pc}{hr}$

$v_{34m} = 0 \frac{pc}{hr}$

Capacity Checks

	Actual	Maximum	LOS F?
V_{FO}	3543	4600	"No"
V_{R12}	3543	4600	"No"

$CapacityChecks_m =$

Level-of-Service Determination (if not F)

$$D_R = 5.475 + 0.00734\, v_R + 0.0078\, v_{12} - 0.00627\, L_A$$

$D_{Rm} = 28.1 \frac{pc}{mi \cdot ln}$

$LOS_m =$ "D" (Exhibit 25-4)

Speed Estimation

$M_S = 0.388$ (Exhibit 25-19)

$S_{Rm} = 53\,mph$ (Exhibit 25-19)

$S_{Om} = 0\,mph$ (Exhibit 25-19)

$S_m = 53\,mph$ (Exhibit 25-14)

Diverge Areas

Estimation of v_{12}

$$v_{12} = v_R + (v_F - v_R) \cdot P_{FD}$$

$L_{EQd} = 0$ (Equation 25-8 or 25-9)

$P_{FD} = 0$ using $Equation_d = 0$ (Exhibit 25-12)

$v_{12d} = 0 \frac{pc}{hr}$

$v_{23d} = 0 \frac{pc}{hr}$

$v_{34d} = 0 \frac{pc}{hr}$

Note: the display of v_{23} and v_{34} is additional to the HCM worksheet

Capacity Checks

	Actual	Maximum	LOS F?
V_{FI}	0	0	0
V_{12}	0	0	0
V_{FO}	0	0	0
V_{R12}	0	0	0

$CapacityChecks_d =$

Level-of-Service Determination (if not F)

$$D_R = 4.252 + 0.0086\, v_{12} - 0.009\, L_D$$

$D_{Rd} = 0 \frac{pc}{mi \cdot ln}$

$LOS_d = 0$ (Exhibit 25-4)

Speed Estimation

$D_S = 0$ (Exhibit 25-19)

$S_{Rd} = 0\,mph$ (Exhibit 25-19)

$S_{Od} = 0\,mph$ (Exhibit 25-19)

$S_d = 0\,mph$ (Exhibit 25-15)

Figure 60. Output results calculated using the original equation of v_{12}

Merge Areas

Estimation of v_{12}

$$v_{12} = v_F \cdot P_{FM}$$

$L_{EQm} = 0$ (Equation 25-2 or 25-3)

$P_{FM} = 1$ using $Equation_m = 0$ (Exhibit 25-5)

$v_{12m} = 1917 \frac{pc}{hr}$

$v_{23m} = 0 \frac{pc}{hr}$

$v_{34m} = 0 \frac{pc}{hr}$

Diverge Areas

Estimation of v_{12}

$$v_{12} = v_R + (v_F - v_R) \cdot P_{FD}$$

$L_{EQd} = 0$ (Equation 25-8 or 25-9)

$P_{FD} = 0$ using $Equation_d = 0$ (Exhibit 25-12)

$v_{12d} = 0 \frac{pc}{hr}$

$v_{23d} = 0 \frac{pc}{hr}$

$v_{34d} = 0 \frac{pc}{hr}$

Note: the display of v_{23} and v_{34} is additional to the HCM worksheet

Capacity Checks (Merge)

	Actual	Maximum	LOS F?
V_{FO}	3543	4600	"No"
V_{R12}	2543	4600	"No"

$CapacityChecks_m =$

Capacity Checks (Diverge)

	Actual	Maximum	LOS F?
V_{FI}	0	0	0
V_{12}	0	0	0
V_{FO}	0	0	0
V_{R12}	0	0	0

$CapacityChecks_d =$

Level-of-Service Determination (if not F) (Merge)

$$D_R = 5.475 + 0.00734\, v_R + 0.0078\, v_{12} - 0.00627\, L_A$$

$D_{Rm} = 20.3 \frac{pc}{mi \cdot ln}$

$LOS_m = "C"$ (Exhibit 25-4)

Level-of-Service Determination (if not F) (Diverge)

$$D_R = 4.252 + 0.0086\, v_{12} - 0.009\, L_D$$

$D_{Rd} = 0 \frac{pc}{mi \cdot ln}$

$LOS_d = 0$ (Exhibit 25-4)

Speed Estimation (Merge)

$M_S = 0.303$ (Exhibit 25-19)

$S_{Rm} = 54.5\ mph$ (Exhibit 25-19)

$S_{Om} = 0\ mph$ (Exhibit 25-19)

$S_m = 54.5\ mph$ (Exhibit 25-14)

Speed Estimation (Diverge)

$D_S = 0$ (Exhibit 25-19)

$S_{Rd} = 0\ mph$ (Exhibit 25-19)

$S_{Od} = 0\ mph$ (Exhibit 25-19)

$S_d = 0\ mph$ (Exhibit 25-15)

Figure 61. Output results calculated using the modified equation of v_{12}

CHAPTER 8

CONCLUSIONS

The Highway Capacity Manual offers a collection of methodologies and techniques for estimating the capacity and evaluation of the level of service for highway, street and transit facilities (HCM 2000). Mathcad worksheets were developed to replicate the computational procedures of the HCM. Five chapters were implemented including Signalized Intersections (Chapter 16), Unsignalized Intersection (Chapter 17), Basic Freeway Segments (Chapter 23), Ramps and Ramps Junctions (Chapter 25) and Transit (Chapter 27).

Although the Mathcad worksheets maintain the format of the HCM worksheets where possible, in some cases the Mathcad worksheets reflect the flow of computations required by Mathcad.

The most important advantage of using Mathcad is the transparency of the algorithms. This allows users to explore the impact of changes in input values and computational algorithms.

The worksheets and the embedded annotation will ensure knowledge preservation as the HCM subcommittee membership changes.

An expert panel provided a positive review of draft versions of the worksheets and their replication of the HCM procedures. During this same review, several significant issues in the procedures themselves were identified that will be addressed through the appropriate subcommittees.

It is anticipated that the further use and development of the chapters by the HCM subcommittees will lead to a better understanding of the HCM procedures and their presentation to the users and will result in a more robust manual for the professional community that relies on the HCM.

Once approved by the HCM subcommittees, the worksheets can be used to develop additional examples and sample problem sets for use by third party developers for the validation of their software packages.

APPENDIX A

SIGNALIZED INTERSECTIONS WORKSHEET

This appendix includes the Signalized Intersections worksheets. All background calculations are displayed.

See Signalized Intersections worksheets.

APPENDIX B

UNSIGNALIZED INTERSECTIONS WORKSHEETS

This appendix includes the Two-way stop-controlled intersection (TWSC), All-way stop-controlled intersection (AWSC) and Roundabouts worksheets. All background calculations are displayed.

See TWSC Intersections worksheets.

See AWSC Intersections worksheets.

See Roundabouts worksheets.

APPENDIX C

BASIC FREEWAY SEGMENTS WORKSHEETS

This appendix includes the Operational and Planning of Level of Service (LOS), Design and Planning of the Number of Lanes Required (N), and Design and Planning of the Flow Rate Achievable (v_p) worksheets. All background calculations are displayed.

See Basic Freeway Segments (LOS) worksheet.

See Basic Freeway Segments (N) worksheet.

See Basic Freeway Segments (v_p) worksheet.

APPENDIX D

RAMPS AND RAMPS JUNCTIONS WORKSHEET

This appendix includes the Ramps and Ramps Junctions worksheet. All background calculations are displayed.

See Ramps and Ramps Junctions worksheet.

APPENDIX E

TRANSIT WORKSHEET

This appendix includes the Transit worksheet. All background calculations are displayed.

See Transit worksheet.

REFERENCES

Mathcad 2001i user's guide with reference manual. (2001). MathSoft Engineering & Education, Inc., Cambridge, MA.

Transportation Research Board. (2000). *Highway Capacity Manual*. National Research Council, Washington, D.C.